THE GEOLOGICAL MAP

By the Same Author

'DIP AND STRIKE PROBLEMS,
MATHEMATICALLY SURVEYED'

The Geological Map

An Elementary Text Book for Students of Geography and Geology

KENNETH W. EARLE
D.Sc. (Lond.), F.G.S.

WITH FORTY-ONE DIAGRAMS

METHUEN & CO. LTD., LONDON
11 New Fetter Lane, E.C.4

First published May, 1936
Reprinted 1952, 1960, 1965
Printed in Great Britain by
John Dickens and Co Ltd, Northampton
Catalogue no 02/2861/69
1.4

PREFACE

It has of recent years become the practice in Universities and University Colleges to insist that geography students who are candidates for final examinations shall have had at least an elementary training in the interpretation of geological maps.

The author's objective in writing these pages, therefore, has been to produce a book which, by the use of only the most simple language, and by the suppression of all superfluous detail, shall be intelligible to students of geography and geology alike. It should be supplemented in the case of senior students in geology by more advanced books, such as Miss Elles's *The Study of Geological Maps*, and by maps such as those reprinted from the Natural Science Tripos by the Cambridge University Press.

The author's chief difficulty in writing this book has been that of every one who attempts to write on the subject of maps, namely to produce a book which is both easy to handle, and within the reach of even the elementary student's pocket. With this object in view he has avoided including any large scale maps and has contented himself with reference to, and description of such maps as are easy of access in any College Geological Department. In some cases reference has also been made to folding maps in the *Quarterly Journal of the Geological Society*, or the *Proceedings of the Geologists' Association*, since these are often more readily accessible than the Old Series (hand-coloured) maps of the Geological Survey.

The writer is well aware of the objections that will be raised to this method of procedure, namely that in general it is not possible for the student to take maps away with him to study at home, and that he is either too busy or too indolent to hunt them up in his own College libraries and study them on the spot side by side with the book itself. But under the circumstances it seems the best compromise that can be effected.

The chief method of illustration used, therefore, is that of solid models. By this means the student is able to view any geological structure not only from the aspect of the surface map, but also simultaneously in sections both in the direetions of the dip and the strike of the strata. These models have been supplemented by small diagrams in the text, so that it has been possible to preserve the normal octavo size of the volume.

BERKHAMSTED,
November, 1935

CONTENTS

(Matter in small type is intended to be omitted at a first reading.

All map references given are to the published sheets of the Geological Survey, unless otherwise stated.)

CHAPTER I

INTRODUCTORY

THE rocks that comprise the earth's surface are divided primarily into three types: *igneous*, *sedimentary* and *metamorphic*.

The *igneous* rocks are those which have solidified from a molten magma, either at the surface, like a lava, or below the ground under pressure. They are crystalline rocks and generally form amorphous bodies, intruded into or extruded through the sedimentary rocks. Although, as at present distributed on the earth's surface, they may be of any age, they largely constitute the fundamental complex of the earth's crust, and it is to them that all the other rocks owe their derivation. They are, by their very nature, unfossiliferous.

The *sedimentary* rocks, as their name implies, were for the most part laid down under water, though it is convenient here also to include those deposits which have been formed by subaerial agencies, such as wind, ice, frost, &c. The true sediments have all been formed by the destruction of previously consolidated igneous or sedimentary rocks, or from the igneous rocks of the fundamental complex. The detritus so formed has been carried down by rivers and deposited in inland lakes or the open sea. Subsequent elevation of the sea or lake floor, or the retreat of the sea, have caused their consolidation at the surface into compact rocks.

The *metamorphic* rocks are those rocks, either originally igneous or sedimentary, which have been altered by contact with the molten igneous rocks, or by excessive and sustained earth movements, causing chemical alteration of the constituent minerals or structural deformation of the rocks themselves.

The igneous and metamorphic rocks are comparatively unimportant for those to whom this book is addressed, and will be relegated to Chapter VII. We shall proceed to discuss the structure of the sedimentary rocks and their development and distribution on the geological map.

THE SEDIMENTARY ROCKS

(1) THE SOLID DEPOSITS

The true sediments, having been laid down under water, have been settled by gravity, and will therefore tend to be consolidated horizontally. The grading of the constituent particles in the deposit will cause the development of *planes of lamination*, along which the consolidated rock will tend to split.

Suppose now, that as a result of earth movements the sea retreats or the land rises vertically; the deposit will be raised above the sea and cemented into a solid rock. On reversal of the process the deposit is submerged below the sea again and a new set of sediments is laid down again on the top of the existing one. It is possible that the first deposit was constituted largely of calcium carbonate in the form of limestone, whereas the second, owing to changed topographical conditions and to the fact that the material has been derived from a different source, will consist largely of siliceous material in the form of sandstone. We shall thus have different types of deposit separated by a horizontal junction or *bedding plane*.

Such bedding planes will reveal, in the form of fossils, traces of the animal and vegetable life that inhabited the local waters and fell to the floor of the sea or lake at death. The deposit may, in fact, consist very largely of the comminuted shells of such animals. The possible presence of fossils, therefore, is an important respect, though it is not particularly relevant to the student of geological maps, in which the sedimentary rocks differ from the igneous.

It is obvious that the processes of submergence or elevation described above may be repeated indefinitely. The

result will be that we shall get a series of stratified deposits or *strata*, one above the other, which are all *conformable*, i.e., all having their bedding planes parallel, but of different thicknesses according to the rate of deposition and the time interval over which each particular deposit has been in the process of formation.

The individual strata may be named lithologically, according to the chemical nature of the constituent material, or stratigraphically, according to the historical order in which they have been laid down. Considered historically,

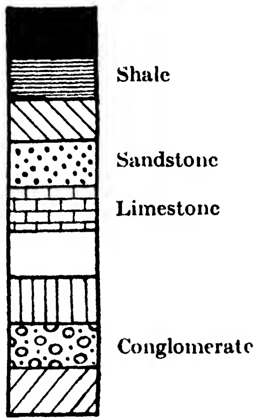


FIG. 1

they are divided primarily into Eras (Groups); these are further subdivided into Periods (Systems), and these finally into Epochs (Series). Each of these Eras, Periods or Epochs is characterized by its own particular suite of fossils, and in some cases by definite lithological horizons, e.g., the Coal Measures, from which the stratigraphical age may be gauged.

Any *strata index* on a geological map will indicate the strata exposed on the map as they would appear if all developed in their normal order in any vertical bore hole; this, however, for reasons to be seen in the sequel, is an ideal

condition rarely fulfilled in actual practice. The youngest strata will, therefore, appear at the top of the column, since they have been consolidated last, the oldest at the bottom.

The column may be drawn to scale, to indicate the relative thicknesses of the various strata, as in the more modern maps of the Geological Survey, or else the different strata are drawn diagrammatically in blocks of equal dimensions, as shown in fig. 1. If the map is coloured, the index will be coloured to match; if the map is produced in black and white a diagrammatic form of shading may be used. Some writers place store on special types of shading to indicate special types of rock (fig. 1), but the matter is entirely arbitrary. On the published maps of the Geological Survey each stratum carries a distinctive letter, as an aid to differentiating similar shades of colour.

(2) THE SUPERFICIAL DEPOSITS

The *superficial deposits* are those deposits which have been accumulated by wind, frost, ice, &c., as well as the alluvial material brought down and deposited in the valleys or flood plains of rivers. They are superficial in the sense that they form no part of the true stratified sequence, having been formed of materials carried under subaerial agencies in times geologically recent from other areas into the places where they are now found. They will, therefore, not be so homogeneous as those rocks which have been formed ' in situ,' and will show no true stratification like the deposits laid down under the sea. They will contain no indigenous fossils and their boundaries will be quite independent of those of the true strata. Examples of such deposits are glacial boulder clay, screes due to frost action, recent sand dunes, river alluvium, peat deposits, raised beaches, &c.

Such accumulations, being newer than the true stratified or *solid rocks*, will be placed in a separate column above and detached from the column of solid strata in any index at the margin of a geological map. The alluvial deposits generally carry a symbol like a swallow, while in the case of glacial deposits the direction of the movement of the ice, as

indicated by the glacial striae, is shown by an arrow of a special type.

The superficial deposits are always inserted last in drawing a geological section across a map.

GEOLOGICAL SURVEY MAPS

Two types of map are issued by the British Geological Survey, designated respectively *Drift* and *Solid* maps. The Drift map is a map showing the distribution of the various deposits exactly as they are at the present time. The Solid map indicates the surface distribution of strata as they would appear if all the superficial deposits were cleared away. It stands to reason that the drift map will be the map required by the farmer and agriculturist, the solid map that required by the mining geologist and prospector.

According to the relative importance of the two types of deposit, any areal map may be published in either the solid or drift editions. For some of the heavily glaciated areas both solid and drift editions are on sale, and it is an instructive lesson for the student to compare the two editions side by side. An excellent example of this contrast is shown in the Holy I. Sheet of the One-inch (New) Series. It will be evident that the solid maps are those best calculated to reveal the true geological structure of the district, and are therefore of most utility to the student of geological maps.

In some cases, e.g., Scotland, one-inch, Sheet 22, Ayrshire north, the Geological Surveyors are preparing yet another edition, known as the Soil Texture Map.

The original Geological Survey maps on the one-inch scale were issued, and are still in all cases obtainable, hand-coloured. As the resurvey of the country proceeds, these are gradually being replaced by up-to-date colour-printed maps. Apart from the fact that their expense makes the hand-coloured maps (Old Series) difficult of access, the absence from them of contouring and other features makes them much less useful to the student than the more up-to-date colour-printed (New Series) maps.

There is also a colour-printed map on the quarter-inch scale, and this is available for all districts in England and for many districts in Scotland; some of the counties are published in

both drift and solid editions. This map naturally does not carry the same amount of detail as that on the one-inch scale; from the fact that it is not contoured and carries no information as to the dip of the strata, throw of the faults, &c., it is not particularly useful for the drawing of sections.

TABLE OF STRATA

The student should make himself familiar with the following list of British formations. The table is neither complete nor entirely systematic in arrangement, but it includes all those names most likely to be found on British geological maps. In accordance with the principle laid down on page 3, the strata are in their normal order, the newest at the top of the table, the oldest at the bottom.

ERA	*SYSTEM*	*SERIES OR EPOCH*
	Recent	
	Pleistocene	Glacial deposits.
Tertiary	Pliocene	The Crag Formations.
	Oligocene	(Freshwater)
	Eocene	Barton beds. Bracklesham beds. Bagshot beds. (Sands and clays).
		London Clay.
		Woolwich and Reading beds (Clays).
		Thanet Sand.
Mesozoic (Secondary)	Cretaceous	Chalk (Earthy limestone).
		Upper Greensand.
		Gault (Clay).
		Lower Greensand.
		Wealden (Freshwater).
	Jurassic	Purbeck (Freshwater).
		Portland beds (Limestone).
		Kimeridge Clay.
		Corallian (Impure limestones).
		Oxford Clay.
		Oolites (Limestones).
		Lias (Shales).
		Rhaetic (Shales).
	Triassic	Keuper Sandstone and Marl.
		Bunter Sandstone and Pebble Beds.
Upper Palaeozoic	Permian	(Includes the Magnesian limestone)
	Carboniferous	Coal Measures.
		Millstone Grit.
		Yoredale beds (Shales and limestones).
		Carboniferous Limestone.
	Devonian	(Includes the Old Red Sandstone)

ERA	*SYSTEM*	*SERIES OR EPOCH*	
Lower Palaeozoic	Silurian [1]	Ludlow beds. Wenlock beds. Llandovery beds.	(Sandstones, shales, and massive limestones).
	Ordovician [2]	Bala beds. Llandeilo beds. Arenig beds.	(Mostly shales, slates, and impure limstones).
	Cambrian	(Slates and grits).	
	Pre-Cambrian	(Unfossiliferous sediments, lavas, schists, &c.)	

[1] Called Upper Silurian on the original one-inch (Old Series) maps of the Geological Survey.
[2] Called Lower Silurian on the original one-inch (Old Series) maps of the Geological Survey.

CHAPTER II

ON OUTCROPS

ON THE DISTRIBUTION OF STRATA ON A GEOLOGICAL MAP

UNDER the conditions of deposition we have postulated, giving rise to a series of horizontally stratified beds resting one on top of another, it follows that, if the ground were flat, the whole surface of the country would be composed of one sort of rock and we could tell nothing of the underlying rocks without drilling.

If, as a result of denudation, however, the ground be undulating, it is obvious that various members of the sequence will appear or *crop out* at the surface. It is clear

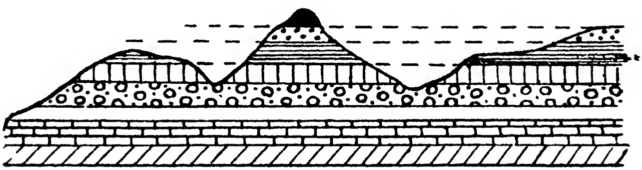


FIG. 2.—Section through Horizontal Strata

from a consideration of fig. 2 that the newest beds will form rings round the crests of hills and the older beds will occupy the valley floors. The number of strata exposed on any one hill summit will further depend on the height of the ground relative to that of the neighbouring summits. (See also p. 14.) For instance, in the figure the bed shaded black occurs on the central hill only, as both the neighbouring hills have been denuded down below the base of that bed.

It follows as a corollary to the above that, unless there has been extensive folding, the newer beds will tend to occur on the higher ground. There is an important exception in

the case of certain superficial deposits, such as River terraces (fig. 3). As the river bed is successively overdeepened along the lines PQR, STV, WZY, the accompanying alluvial deposits will be laid down successively nearer the centre of the valley, and on the geological map the earliest formed

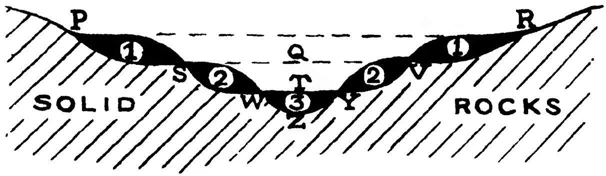


FIG. 3.—Section through River Terraces

alluvial deposits will tend to occupy higher ground than those formed subsequently.

It seldom happens that the strata remain horizontal over any considerable distance. They have generally been tilted by subsequent earth movements and sometimes folded,

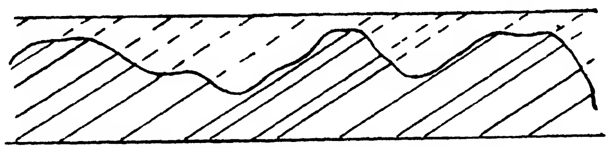


FIG. 4.—Section through Inclined Strata

faulted, and invaded by igneous masses. If the strata are inclined, we shall get a varied exposure of rocks at the surface, whether the ground surface be horizontal or undulating (fig. 4). Their distribution will be shown on a geological map.

DIP, STRIKE AND OUTCROP

In order to determine the trend of the boundaries of the various deposits on a geological map, it is necessary, in addition to knowing the shape of the country, to have some means of defining the position of any particular stratum (considered for this purpose a plane surface) in space.

Now the position of a plane in space is determined in two ways—either by knowing the position of any three points on it, or by knowing the position of one point on it, given the maximum slope (in direction and amount) of the plane at that point.

For immediate purposes the second of these methods is the most important, and we shall therefore define the maximum slope of any inclined stratum, measured from the horizontal, as the *true dip*, or, more shortly, as the *dip* of the stratum. It is stated in direction and amount, thus: 10° ESE. On the geological map the direction is indicated by an arrow (all maps being oriented north and south, unless otherwise stated), with the amount quoted beside it, thus: ↗ 10°. Dips indicated on a geological map, unless otherwise stated, are those at the point where the stratum actually cuts the ground surface. Underground dips, as determined by mine workings, may be indicated in a special manner. Horizontal strata are indicated thus: +, vertical strata thus: —▮—.

Dip is measured in the field by an instrument known as a clinometer. This consists of a rule, hinged in the centre, the two halves carrying spirit levels on their upper edges when the instrument is doubled up, and bearing also a compass on one of the arms and a brass scale, graduated in angles, at the hinged end. To take a reading the instrument is placed with its lower edge on an exposed bedding plane of the rock, and then moved round, keeping the upper edge level, until the position is found where the angle from the horizontal, as measured on the graduated brass scale, is a maximum. The angle found is the required angle of dip and its direction is measured by means of the attached compass.

In practice the surface of the stratum is generally so irregular that it will be necessary to take several readings and work out the mean. A further difficulty arises when, as sometimes happens, only the under surface of the bedding plane is visible, as it is then impossible to see when the lower edge of the clinometer is level.

It is not always possible to measure the true dip in the field. For instance, in fig. 13, p. 23, the dip of the upper set of strata, as viewed along the back edge of the model, appears to be downhill towards the left, whereas, viewed along the side edge, it appears to be downhill towards the right. The true dip is,

however, towards the corner of the model. Given two such *apparent dips*, as viewed in any two given directions, say in adjacent faces of a quarry, it is possible mathematically to determine the true dip, if the directions of the two apparent dips are known. In actual fact it is almost always possible, however, provided the section is actually accessible—i.e., not viewed from a boat or otherwise—to find a projecting ledge of rock sufficiently large to apply the clinometer.

The horizontal line at right angles to the direction of true dip is known as the *strike*. Since there are other possible directions at right angles to the direction of dip, it is important to emphasize the word ' horizontal ' in the definition. The relationship between dip and strike is, in fact, exactly that between ground slope and contour. The actual trace of the stratum where it meets the ground surface is known as its *outcrop*. The term is also sometimes used to signify all the surface area occupied between the top and bottom of the bed ; the two meanings are synonymous if the bed be considered of negligible thickness.

It follows that the direction of strike is always a straight line, while the outcrop will be a straight or curved line, depending on the dip and the surface relief of the country.

The relationship between dip, strike and outcrop is shown in fig. 5.

Note that, if the ground surface is horizontal, one reaches the newest beds as one walks in the direction of dip, the oldest as one walks in the contrary direction.

Note also that the strata will always appear horizontal in any section along the strike. This is an important point to remember when drawing sections across geological maps at right angles to the direction of full dip.

Note further that the outcrop will only coincide with the strike when :

(1) the beds are vertical, the outcrop being now a straight line, whatever the surface relief,[1] or

[1] The student must remember that a map represents a bird's-eye view of the country, so that all outcrops must be pictured as *projected* on to a horizontal plane. For this reason outcrops which appear as straight lines when projected on to a horizontal plane, will appear as slightly curved lines in a side view of a relief model.

(2) the ground is horizontal, the outcrop being again a straight line, whatever the amount of the dip.

It is obvious that this must be so, for although the strike is always a straight line (p. 11), only in the above cases can the outcrop be so. In every other case the outcrop will be a curved line, and the amount of deviation of strike from outcrop will depend on the varying relationship between the

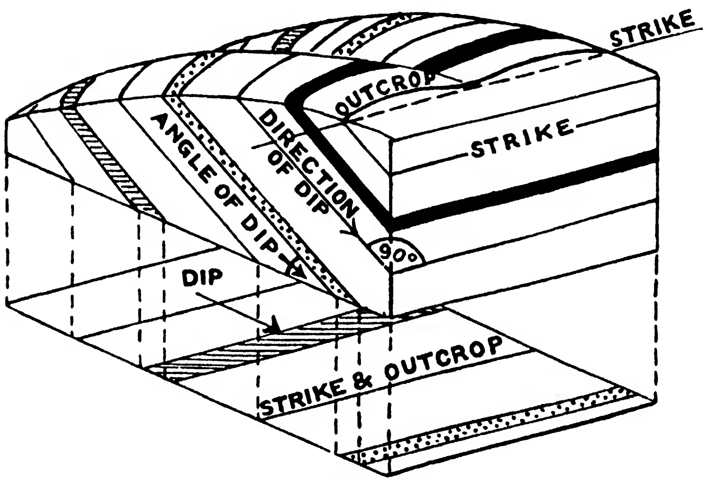


Fig. 5.—Diagram illustrating Dip, Strike and Outcrop

amount and direction of the dip and of the slope of the ground.

The relationship can best be understood by reference to fig. 6. In each case the surface relief is the same, but the dip of the strata has been varied. The ground contours have been inserted as dotted lines.

SUMMARY OF CASES

A. Ground Horizontal

The outcrops are always straight lines, whatever the dip. This case is illustrated in fig. 5.

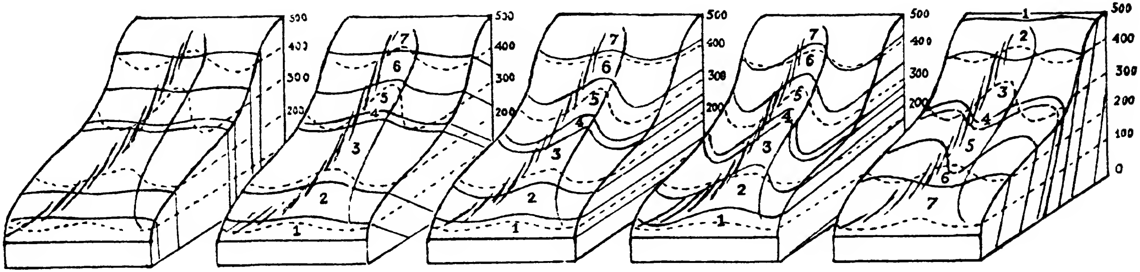


FIG. 6.—Outcrops in a Valley

a. Beds vertical. *b*. Dip in opposite direction to slope of ground. *c*. Beds horizontal. *d* Dip downstream, at a less angle than slope of ground. *e*. Dip downstream, at a greater angle than slope of ground.

Exs. Nottinghamshire and West Lincolnshire. Quarter-inch, Sheets 7 and 11, and Stanford's Geological Atlas, Maps 20 and 24.

B. Ground Undulating

(1) Beds vertical.

The outcrops follow straight lines across the country, irrespective of the ground contours.[1]

Exs. I. of Wight. Special Sheet (N.S.) and Swanage. Sheet 343 (N.S.). The vertical Cretaceous strata run in straight lines through the centre of the map in an E–W. direction. Contrast this with the sinuous outcrops in the southern part of the map, where the dip is flatter.

(2) Beds dipping in the opposite direction to the ground-slope.

The outcrops point upstream.

Ex. This feature is well displayed in the streams flowing west down the Westmorland Pennine escarpment; it is very well illustrated in the map accompanying the paper by J. Selwyn Turner in *Proc. Geol. Assoc.*, Vol. XXXVIII, 1927.

(3) Beds horizontal.

The outcrops follow the contours in parallel bands round the hill slopes.

Exs. Ingleborough. Sheet 97 SW. (O.S.). The various limestone beds form rings round the hill-tops, with the newest bed—the Ingleborough Grit—at the summit. Note that the relative heights of the various hills are indicated by the number of strata present.

Sidmouth. Sheets 326 and 340 (N.S.).

(4) Beds dipping downstream, and at a less angle than the slope of the valley.

The outcrops point upstream.

Exs. Aylesbury. Sheet 238 (N.S.). The outcrops of the Middle Chalk and Chalk Rock point upstream, as the dip is generally downstream at a low angle.

Reigate. Sheet 286 (N.S.).

---

[1] See footnote on p. 11.

(5) Beds dipping downstream, and at a greater angle than the slope of the valley.

The outcrops point downstream.

Exs. Egton. Sheet 43 (N.S.). The outcrops of the Oölites along the southern margin of the map all point towards the mouths of the rivers. The same is true at the north end of the map, but to a less conspicuous extent.

The Jurassic escarpment in Sheet 15 of the quarter-inch map shows splendidly the variation in outcrop when the dip is downstream at a less, the same and a greater angle than the slope of the valley.

Rule. The outcrops in a valley will always point *upstream unless the dip is in the same direction as the slope of the valley, and at a greater angle*, when the reverse occurs.

In studying a geological map, therefore, where the dips are few or wanting, the student should always look for the outcrops which point towards the mouths of the rivers, as these will always indicate a fairly steep dip in that direction.

Note that in this case the beds are in inverted order, so that walking upstream one reaches the *newer* beds first; in all other cases one reaches the *older* beds first. When the strata are vertical, it is obviously impossible to determine their correct order.

Note also that the smaller the dip, the greater is the deviation of strike from outcrop, and vice versa.

Generally speaking, the smaller the dip, the more sinuous the outcrop; the higher the dip, the more nearly do the outcrops approach straight lines. The maximum sinuosity, however, is not when the strata are horizontal, but when the dip of the beds is the same as the slope of the valley, and in the same direction. This very special case has not been figured.

WIDTH OF OUTCROP

It is important that the student should notice how the width of outcrop of any given stratum varies with the dip.

Fig. 7 shows that, provided the thickness of the bed is constant and the ground is considered horizontal, the width of outcrop (XY) is a minimum when the bed is vertical (being

then, in fact, equal to the true thickness of the bed, XZ), and that as the dip decreases the width of outcrop increases.

Ex. In the I. of Wight sheet note the narrowness of the outcrops of the Cretaceous strata in the vertical limb of the fold, compared with those in the flat part of the anticline to the south.

In the same way, if the stratum remains horizontal, or nearly so, its outcrop will decrease in width as the ground slope increases, till we reach the case of the vertical cliff, where the width of outcrop is nil (p. 72).

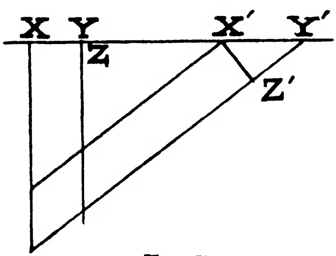


FIG. 7

The student must, therefore, not assume that there is thickening of a stratum because its width of outcrop varies in different parts of the map, unless he has first considered whether this may not be due to change of dip or change of slope.

ON THE PLOTTING OF OUTCROPS

It is obvious from figs. 5 and 6 that the strike of a constantly dipping bed on a contoured map will always be a straight line joining points where the bed crops out at the same altitude. This affords a simple method of determining the strike from a contoured map.

For instance, in fig. 8, suppose a constantly dipping stratum crops out at the surface at the points P, Q, on the 400-ft. contour. PQ is then the strike of the stratum, and any other points, such as R, S, where PQ again cuts the 400-ft. contour, will be further points of outcrop of the bed.

We cannot say any more about the dip, except that it is at right angles to PQ, either north or south, unless we have another point of outcrop, T, on a different, say the 300-ft., contour. Since the line through T, parallel to PQ, is a strike line for the 300-ft. contour, wherever it cuts the 300-ft. contour again will be another point of outcrop, V.

The bed is at a higher altitude along PS than along TV. The dip is, therefore, in the direction AB, and not BA.

Since the dip remains constant, such strike lines for successive contours must be parallel and equidistant, in exactly the same way that the ground contours will be equidistant where the ground slope remains constant. By covering the map with such *stratum contours* the same distance apart,

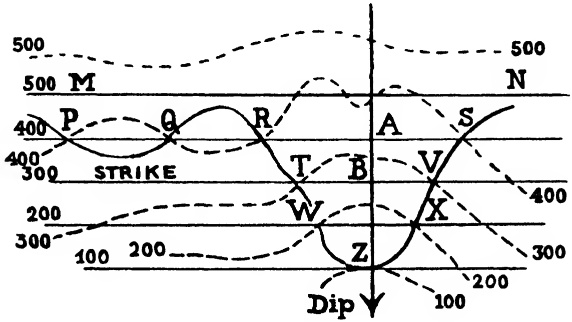


FIG. 8

and numbering them to correspond with the ground contours, we can map in all the points of outcrop for the various ground contours and complete the outcrop diagrammatically over the area of the map. Since MN, the 500-ft. stratum contour, does not cut the 500-ft. ground contour, no points of outcrop occur north of MN.

The completed outcrop is shown in the diagram.

Such stratum contours represent falls in level of the bed of 100 ft., corresponding to the ground contours. If the horizontal scale of the map is given, therefore, we may now calculate the *amount* of the dip. For the bed falls 100 ft. vertically in the horizontal distance AB, say 1000 ft. The dip is, therefore, $\tan^{-1}\frac{100}{1000}$, or $\tan^{-1} 0{\cdot}1$, i.e., 5° 45′.

If the 'borehole thickness' of the bed is given, i.e., the distance between the top and bottom of the bed, as measured in a vertical borehole,[1] we may now map in the other boundary. For instance, suppose the bed in fig. 8 to be 200 ft. thick, and

[1] The true thickness is, of course, measured at right angles to the bedding plane.

the plotted outcrop to represent the base of the bed. Then everywhere along the strike line PQR the top of the bed is at 600 ft. in altitude. By renumbering the stratum contours, therefore, the points where they cut the corresponding ground contours may be marked in and the top of the bed mapped in, just as before.

The problems of plotting outcrops from three isolated points of exposure on *different* contours, and from *one* point of exposure, given the amount, as well as the direction of the dip, have been discussed by the author elsewhere.[1]

The relevance of the following hints will be appreciated by the student who attempts such plotting of outcrops in practice:

(1) Until considerable experience has been obtained each stratum contour should be numbered on the map to correspond with its ground contour.

(2) In mapping the points of outcrop each strike line should be followed *along its entire length* before passing on to the next one. Unless the map is of the very simplest order, points of outcrop will otherwise be missed, and it will not be clear in the sequel how to join them up by a continuous line.

(3) An outcrop must never cross a ground contour except where it is cut by a stratum contour, and vice versa. When such a point is reached the outcrop must cross right over to the other side of both of them.

(4) If ground and stratum contours should touch at any point, the outcrop will become tangential to both at that point, and will return in the same direction without crossing either of them (e.g., the point Z in fig. 8).

(5) There must be no loose ends in the finished outcrop, except at the margin of the map. If two isolated points occur which cannot be joined to the other parts of the outcrop without violating rule (3), a closed outcrop round the summit of a hill or base of a depression is probably indicated.

(6) Ambiguous points are bound to occur. The trend of the outcrop at critical points may sometimes be elucidated by the interpolation of subsidiary ground contours.

[1] K. W. Earle, *Dip and Strike Problems, Mathematically Surveyed,* 1934.

CHAPTER III

ON UNCONFORMITIES

IMAGINE a series of strata, deposited successively below water, so that their bedding planes are horizontal, to become elevated above sea-level and subjected to tilting, so that all the beds have the same dip, and then to be exposed to prolonged denudation. Subsequent submergence below the sea causes a new set of beds to be deposited horizontally round the flanks and across the denuded edges of the former set. Upon renewed elevation above the sea and consolidation under subaerial agencies we shall have two sets of strata,

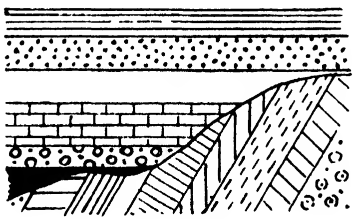


FIG. 9

each set with its individual bedding planes parallel to one another, but the bedding planes of the one set in marked discordance with those of the other. Such a structure is known as an *unconformity* (fig. 9).

In the simplest case the upper series will appear horizontal, but both series may, of course, be subjected to further tilting, in which case the final dip of the lower or older series will give no indication of their dip prior to the deposition of the second set.[1]

[1] It may, however, be mathematically determined, given the final dip, and the direction of the secondary tilt. Vide K. W. Earle, *Dip and Strike Problems, Mathematically Surveyed*, 1934.

If the first series is not tilted from the horizontal position before the deposition of the second series, although separated by a considerable time interval from it, or if the section is viewed along the strike of both series (if both have the same strike), both sets will appear to be horizontal and the unconformity may not be visible. Such an unconformity is known as a *non-sequence* (fig. 11) and can only be detected by information derived from another area, where the missing beds are developed.

The surface along which the two sets of unconformable strata are united is known as the *unconformable junction* ; if a plane, it is known as the *plane of the unconformity*.

If the former set of strata have not been reduced by denudation to the horizontal, the plane of the unconformity

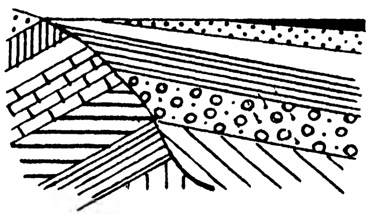


FIG. 10

will not be parallel to the bedding planes of the second set of strata. Each new stratum, as deposited, will extend further and further across the denuded edges of the former set, as the surface sinks further below the sea. Such a set of conditions gives rise to *overlap* (fig. 9).

In such a case some of the beds of the lower series will tend to be concealed at points of the surface and will *thin out* in wedge-shaped outcrops.

Offlap is due to the deposition of the second series on a shelving and *rising* shore-line, so that with retreat of the sea successive deposits recede from the shore-line. In such a case there is in reality a small unconformity below each stratum deposited (fig. 10).

Unless the strike of both series in any unconformity is

the same, the outcrops of the upper series will cut diagonally across or *transgress* the outcrops of the lower series at the surface of the country, or on the geological map.

Note that in any unconformity the newer beds generally have the flatter dip, although there are exceptional circumstances where the reverse is the case (fig. 12).

In any index to the strata on the margin of a geological map the presence of an unconformity should be indicated by a gap in the sequence.

TYPES OF UNCONFORMITY

The various types of unconformity will be seen by reference to the following diagrams.

(1) UNCONFORMITY WITHOUT OVERLAP OR TRANSGRESSION (fig. 11)

None of the upper series of beds is concealed at the surface. STUV is the plane of the unconformity and both

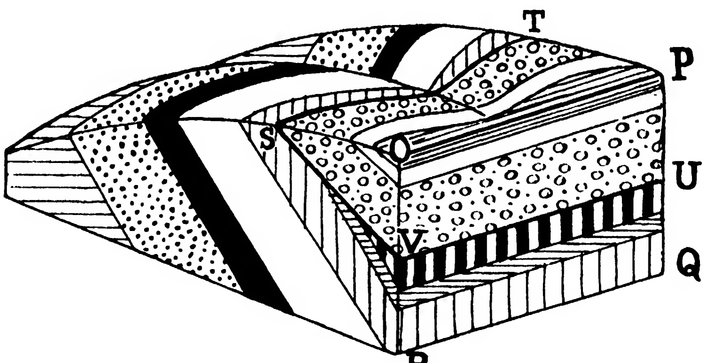


FIG. 11

series have the same strike (parallel to OP); therefore the outcrops remain more or less parallel. The lower series, however, has the steeper dip, hence the outcrops of the upper series are slightly more sinuous than those of the lower. Since the strike of both series is the same, in the

section OPQR both sets of strata appear horizontal and the unconformity is invisible (non-sequence). It could only be detected by noting the sinuosity of the outcrops and the change of dip at the surface. If the ground were horizontal the outcrops of both series would be parallel straight lines and the unconformity could only be detected if the change in dip were actually measurable with a clinometer.

In the extreme case the upper series may be horizontal.

(2) UNCONFORMITY WITH TRANSGRESSION BUT NO OVERLAP

(*a*) *The Strike of both Series is the same*

This is a more advanced stage of (1) (fig. 12).

To make the transgression as pronounced as possible the underlying series has been drawn horizontal, but this, of course, is not necessary. The outcrops of the lower series

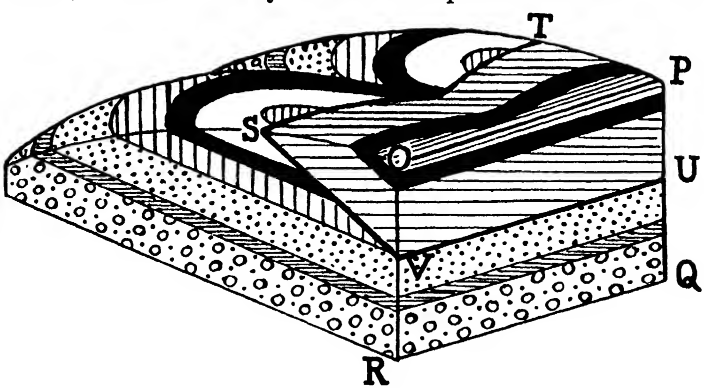


FIG. 12

are far more sinuous than those of the upper series and terminate abruptly against the plane of the unconformity. The outcrops in each series remain parallel. In the section along the strike the unconformity remains a non-sequence.

Note that in this case the upper series has the steeper dip.

In the extreme case the lower series may dip in the reverse direction (downstream), as in fig. 32.

(*b*) *The Strike of the two Series is different* (fig. 13)

The lower series dips at right angles to OPQR, the upper towards the corner O.

In this case the upper series has been deposited on a horizontal floor, so that there is no thinning out in the upper series, all the bedding planes being parallel to the plane of the

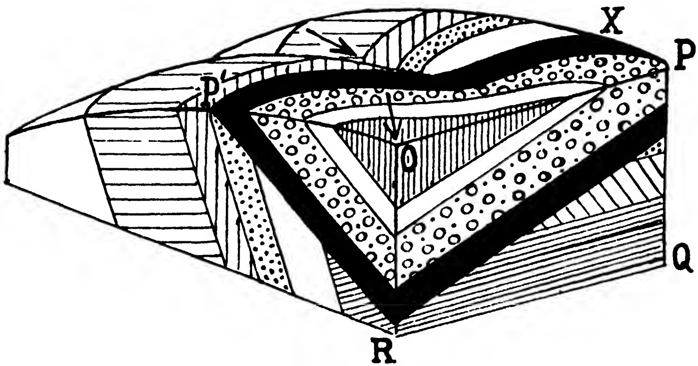


FIG. 13

unconformity. The lower series is, however, transgressed by the upper series along the line of the unconformity, XP′. Owing to the divergence of strike the unconformity is not only visible at the surface, but in both sections as well.

Note that if the strike of a folded series and that of an overlying unconformable series be at right angles, there will still be transgression but no overlap.

(3) UNCONFORMITY WITH TRANSGRESSION OF BEDS AND OVERLAP (fig. 14)

Here the upper series has been deposited on a shelving shore-line, i.e., the plane of the unconformity is not parallel to the individual bedding planes of the upper series. Also the strike is different in the two series. This is the most general case of unconformity and reveals a number of important features.

At the surface the individual outcrops in each series remain parallel to each other. Owing to the divergence of strike, however, there is transgression between the two series, and owing to the fact that the bedding planes of the upper series are not parallel to the plane of the unconformity, there is wedging or *thinning out* of the upper beds against the plane of the unconformity.

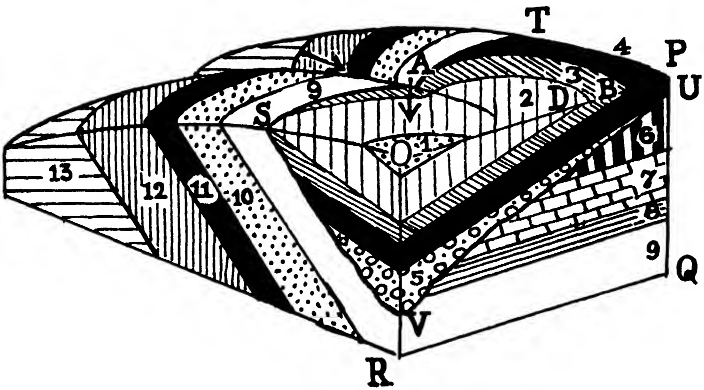


Fig. 14

It is important to note that there is only one unconformity, as seen at the surface, viz., that along the line SAT. There is no unconformity along the lines AB, SD, as well, since the outcrops SD, AB, allowing for a slight variation in ground slope, are parallel. Further, there is no limit to the number of beds that may be over-stepped in this manner. For instance, at the point S bed 2 has overstepped beds 3, 4 and 5 to rest on 9, so that 3, 4 and 5 are not visible at the surface. Beds 4 and 5 were, in fact, never laid down at the point S at all. Beds 6, 7 and 8 of the lower series are also invisible at the surface.

The section OPQR is at right angles to the dip of the lower series and obliquely to the upper series. Therefore the lower series appears horizontal, while the upper series dips towards the corner O; therefore the unconformity is visible in both sections.

An unconformity of this type is also pictured in fig. 33. In this latter case the unconformity is along the line ABGC. There is no unconformity along the lines DBGC and EGC as well.

RECOGNITION OF UNCONFORMITIES

Unconformities may be recognized at the surface or on the geological map by:

(1) Discordance of strike. This is a certain test (figs. 13 and 14).

(2) Discordance of dip, without change of strike. The discordance may be either one of amount (fig. 11) or of direction (figs. 12 and 32). The student must make sure that such a structure is not due to folding.

(3) Transgression of outcrops (figs. 12, 13 and 14). This is a certain test, provided it is clear that such structure is not due to faulting.

(4) Thinning out of the beds (overlap) (fig. 14).

(5) Absence of beds in one area, known to occur in neighbouring areas. For instance, in fig. 12 beds exposed at the surface are not visible in the section OPQR. Hence in the OPQR section an unconformity is deduced along the line UV.

EXAMPLES OF UNCONFORMITIES ON BRITISH SURVEY MAPS

Examples of unconformities on British Survey maps are almost too numerous to mention, but the following representative cases may be cited:

Ingleborough. The unconformity between the Carboniferous Limestone and the Lower Palaeozoic rocks below is strikingly shown in the map accompanying the Survey Guide to the Ingleborough Model, and also in that accompanying the paper by W. B. R. King and W. H. Wilcockson in *Q.J.G.S.*, Vol. XC, 1934. The two series have much the same strike, but the Lower Palaeozoics are folded into anticlines and synclines, so that there is marked transgression but no overlap.

Stoke-on-Trent. Quarter-inch, Sheet 11, one-inch, Sheet 123 (N.S.). The Coal Measures are folded into a series of anticlines

and synclines striking north and south, below the gently dipping Trias. There is thus marked discordance in dip, though not in strike, between the two series, causing the Trias to transgress the various members of the Coal Measures, to rest on the Millstone Grit in the north-east corner of the map.

Oswestry and Wrexham. One-inch, Sheets 121 and 137 (N.S.). The Carboniferous Limestone, striking almost at right angles to the underlying Lower Palaeozoics gives rise to marked transgression. The Trias above is also unconformable on the Carboniferous Limestone.

Mendip Hills. One-inch, Sheet 19 (O.S.). The Trias is unconformable on the Carboniferous Limestone. The Inferior Oolite is also unconformable on the Carboniferous Limestone.

Devizes. One-inch, Sheet 14 (O.S.). Owing to slight discordance in dip between the Cretaceous and underlying Jurassic beds the Gault, between Westbury and Devizes, oversteps the Lower Greensand, Portlandian, Kimeridgian and Corallian rocks, to rest on the Oxford Clay. Further south the Upper Greensand has overstepped the Gault and Lower Greensand to rest on the Kimeridge Clay. This is known stratigraphically as the Cenomanian transgression.

CHAPTER IV

ON FOLDS

HITHERTO we have considered only the question of constantly dipping strata. If this ideal condition were universally fulfilled, our map would merely show a series of more or less parallel outcrops, instead of the complex distribution of strata always met with. The strata are, in fact, usually bent or folded, though their surfaces remain, in general, parallel. These folds are produced largely as a result of pressure, acting from two opposite directions, either horizontally or parallel to the bedding planes, or from one direction only if the other is held by some non-resistant rock mass. As a result of such pressure, if it is not so violent or so long sustained as to cause fracturing by faulting, the rocks will be bent into a series of arches and troughs.

For the sake of argument the rocks which have undergone deformation in this way are considered to be elastic, so that their bedding planes will remain parallel after folding and the strata maintain a constant thickness throughout. In practice the stratum is generally much thicker on the crest of the fold and considerably attenuated in the middle limb.

SYNCLINES AND ANTICLINES

As the arch gives place to the trough there must obviously be a different dip at every point of the limb of the fold. There must, therefore, be areas where the dip is nil. Such areas occur along lines in the direction of the strike of the strata and are known as the *axes* of the folds. The arches are known as *anticlines*, the troughs as *synclines*. An anticline is, therefore, defined as a fold which dips on both sides *away* from a central axis, and a *syncline* as a fold which dips

on both sides *towards* a central axis. The plane containing all the apices is known as the *axial plane* (fig. 15).

Ex. **Simple anticlines and synclines are well seen in the one-inch map of the Cork district (Southern Ireland).**

Note that in any folded series there are two directions of dip, but only one direction of strike. In discussing the structure of a folded series it is, therefore, often more convenient to refer to the direction of strike than to that of the dip.

One of the first difficulties that the student has to over-

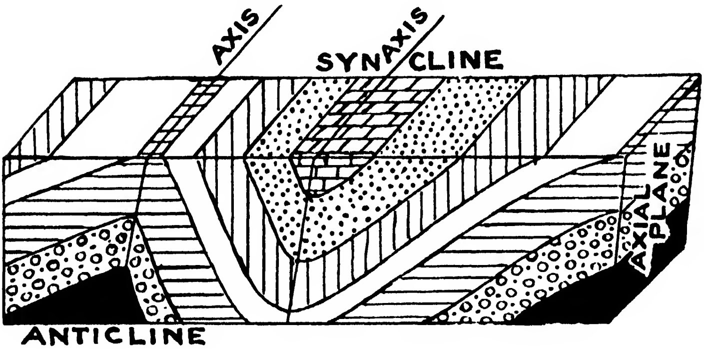


FIG. 15.—Asymmetrical Anticlines and Synclines

come is the tendency to confuse geological with topographical terms. For instance, he must learn at once that the word 'anticline' refers solely to the geological arrangement of the strata, and has no connexion whatever with the terms 'hill' or 'ridge'. In the same way he must not talk of 'valleys' where he means 'synclines', 'dip' where he means 'ground slope', and so on.

Complication is introduced by the development of subsidiary folds and buckles within the main anticlines and synclines. This gives rise to *anticlinoria* and *synclinoria*. *Geanticlines* and *geosynclines* are similar terms, denoting land areas of an anticlinal nature or synclines of deposition, both being folds of great wave-length and low amplitude.

The axial plane will tend to be vertical if the horizontal pressure is slight, and the fold will be symmetrical. With increasing pressure the axial plane will tend more and more towards the horizontal or parallelism with the bedding planes, and the fold will be asymmetrical or overturned.

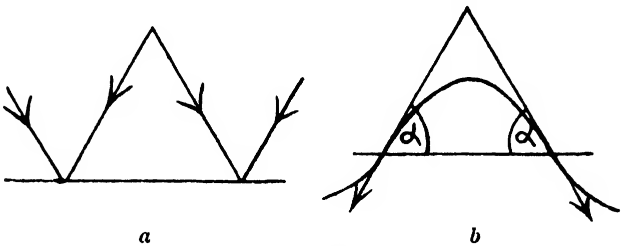


Fig. 16

With the symmetrical fold the amount of the dip is the same on both sides of the axis or, more accurately, at similar horizons on opposite sides of the axis, for in practice the fold seldom shows the idealized V-shaped section pictured in fig. 16 *a*, but rather the curved form of fig 16 *b*.

It may happen that the two outer limbs of a double fold—anticline and syncline—are practically unaltered by the pressures acting on them, but that the central limb is doubled up so as to dip very steeply or vertically. Such a fold is termed a *monoclinal fold* or *monocline*.

Ex. The one-inch Sheet of the I. of Wight shows an excellent example of a monoclinal fold, which is continued in the I. of Purbeck to the west (Sheet 243 (N.S.)).

If the pressure is greater still we get the overturned fold or *overfold*. The characteristic feature of such a fold is that, except immediately adjacent to the apex, the dip is in the same direction on both sides of the axis.

The symmetrical fold, the monoclinal fold and the overfold are illustrated in fig. 18.

If overfolds become closely packed together, so that the dip is not only in the same direction, but equal in amount

on opposite limbs of the fold, we have what is known as *isoclinal folding*. Such folding is illustrated in fig. 17.

It may further happen that in advanced types of overfolding the axial plane approaches the horizontal, so that the rock sheets forming the fold are also horizontal. Such folds are called *recumbent*, and are illustrated in fig. 17.

Note the difficulty in a recumbent fold of telling the correct order of the beds.

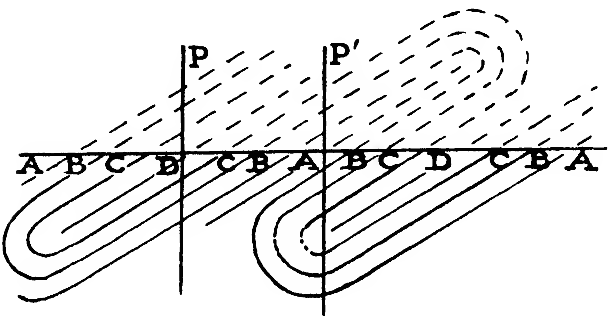


FIG. 17

For instance, in fig. 17, a shaft sunk at P shows the order to be;

D (newest)
C
B
A (oldest).

A shaft sunk at P′, however, shows the order to be;

A (newest)
B
C
D (oldest).

In other words, without reference to other areas where the sequence is more normal, it is not possible to tell which is the anticline and which the syncline,

An abnormal type of asymmetrical folding, characteristic of the Alps, is that known as *fan structure* (fig. 19).

Exs. Overfolding in the tuffs and lavas of the Lake District is well displayed in the maps accompanying papers by J. J. Hartley in *Proc. Geol. Assoc.*, Vol. XXXVI, 1925, and Vol. XLIII, 1932. Isoclinal folds are figured by Miss Elles from the west bank of the River Conway (*Q.J.G.S.*, Vol. LXV, 1909), and from the Tayvallich Peninsula (*Q.J.G.S.*, Vol. XC, 1935,

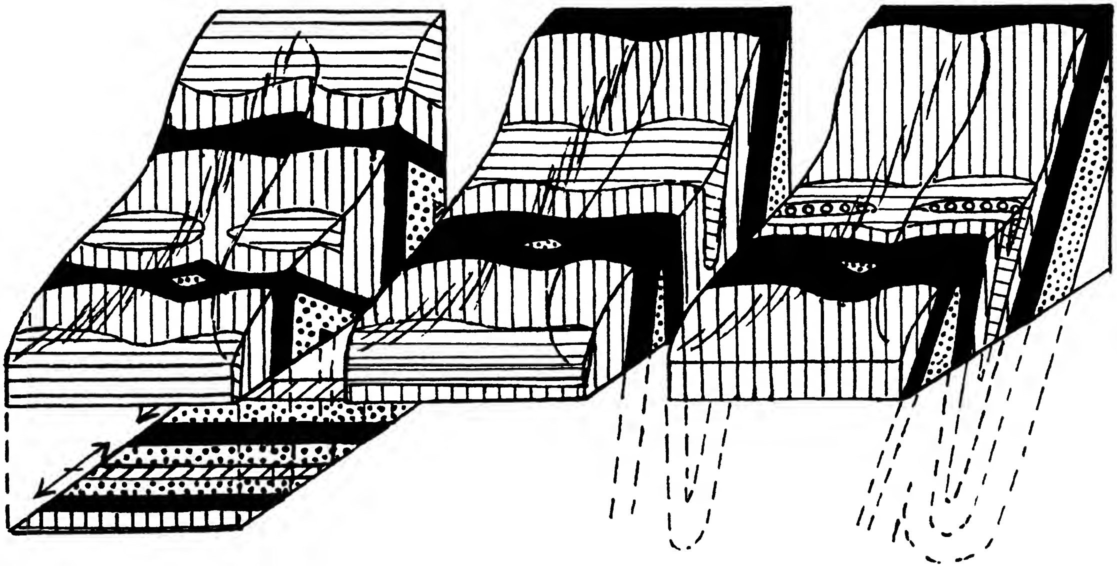


FIG. 18.—Types of Fold

a. Symmetrical anticlines and synclines. *b*. Monoclinal fold. *c*. Overfold.

pl. x), and by T. T. Groom from the Forest of Wyre Coalfield (*Q.J.G.S.*, Vol. LVI, 1900).

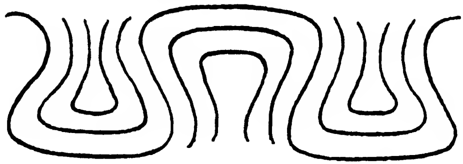


Fig. 19.—Fan Structure

THE NATURE OF THE OUTCROPS OF FOLDED STRATA

If we truncate the anticlines and synclines by a horizontal plane, we shall get a series of outcrops consisting of straight lines, all parallel to the axes of folding (figs. 15 and 18 *a*).

Walking in the direction of the dip, we shall get a repetition of beds, but in the reverse order, and a *gradual* change in dip on either side of every axis. This is in distinction to an unconformity, where there is a *sudden* change in dip, followed by a *different* succession of strata, or to a fault, where we get repetition of the same strata, *without reversal and without change of dip*. Repetition of strata must, in fact, always be interpreted as due to folding, unless actual evidence of faulting is present.

If the fold is symmetrical, the outcrop of any individual bed will be of the same width on opposite sides of the axis. If the fold is asymmetrical, the outcrop will be widest on the side of the fold with the flatter dip (fig. 15).

Note that in a denuded anticline the centre of the sandwich will be occupied by the *oldest* beds, in the syncline by the *newest* beds. This is important for, if the order of the beds is known, it enables us to determine the direction of dip—i.e., whether the fold is an anticline or a syncline; and vice versa, if the dip is known, we can determine the order of the beds.

The ideal picture of parallel outcrops never obtains for very long in actual practice, for folds never continue indefinitely in the same straight line, but tend to die away or be replaced by others 'en echelon'. So that we get 'V-shaped' or 'boat-

shaped' outcrops, the regularity of which depends on the amount and uniformity of the dip.

In any case irregularities in the ground surface are quite sufficient to disturb the parallelism of outcrops. The divergence of outcrops from parallelism is also accentuated by *pitch*, where the axis of the fold no longer remains horizontal. The

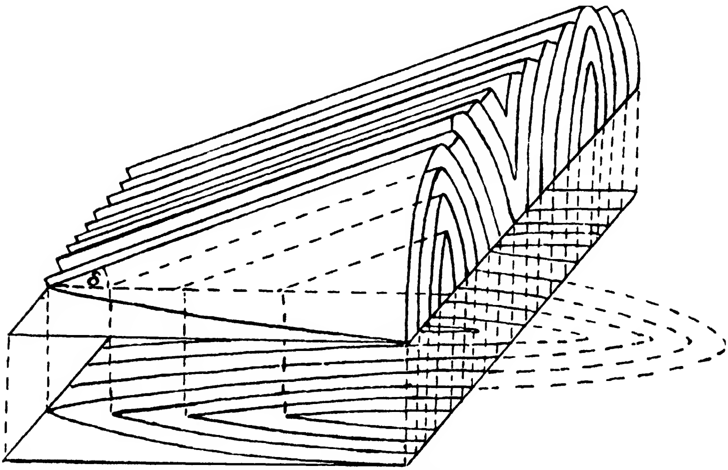


Fig. 20.—Diagram of Pitching Folds

angle of pitch is measured in direction and amount from the horizontal, just as that of a dipping stratum. The result of such pitch is that the outcrops tend to follow a zigzag course (fig. 20), the anticlines pointing in the direction of pitch. This latter feature may, however, be obscured by the surface relief (fig. 23).

Exs. (Pitching folds.) Stoke-on-Trent. Sheet 123 (N.S.) and Cork.

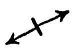
('En echelon' folds.) Moffat. Scotland, Sheet 16 and Mendips, Sheet 19 (O.S.).

The nature of the outcrops of folded strata on an undulating surface is illustrated in three typical cases in fig. 18.

In the case of the symmetrical folds the outcrops tongue up or down stream, according to the relationship between

the dip and the ground slope (p. 13). In the monoclinal fold the outcrops all point downstream, since the dip is in the same direction as the valley slope, except in the central (vertical) limb, where they are quite straight. In the overfold all the outcrops point downstream for the same reason; they are more sinuous and wider apart where the dip is flat than where it is steep.

It is quite a common occurrence for anticlines to form valleys and synclines hills. This is due to the fact that the beds in the anticlinal part of the fold are stretched, while those in the syncline are compressed, so that the anticlines are the more liable to denudation. Thus it rarely happens that tectonic structures are responsible directly for topographic form, as is the case in the Jura, which still retains anticlinal mountains and synclinal valleys.

On the geological map anticlines are indicated by the symbol , synclines by the symbol , the arrows pointing in the direction of dip, the bars indicating the direction of strike.

DOMES AND BASINS

Suppose now that the dip, instead of being from or towards an *axis*, be quaquaversal or concurrent, i.e., in all directions away from or towards a central *point*. We then have the structures known as *domes* and *basins* respectively.

Exactly as the denudation of an anticline gives rise to parallel outcrops, with the oldest beds in the centre, so the denudation of a symmetrical dome on level ground will give rise to circular outcrops, with the *oldest* bed of the sequence in the centre. A symmetrical denuded basin, on the other hand, will show circular outcrops, with the *newest* beds of the sequence in the centre. There is, however, generally elongation of the dome or basin in one direction or another, as in the Weald of Kent or the S. Wales Coal Basin.

Fig. 21 illustrates a dome in plan and section.

Note that in any one given section the structure has the appearance of an anticline; but if the appearance is that of

an anticline in two sections at right angles, the structure must be a dome.

By inversion the diagram may be made to serve to illustrate a basin.

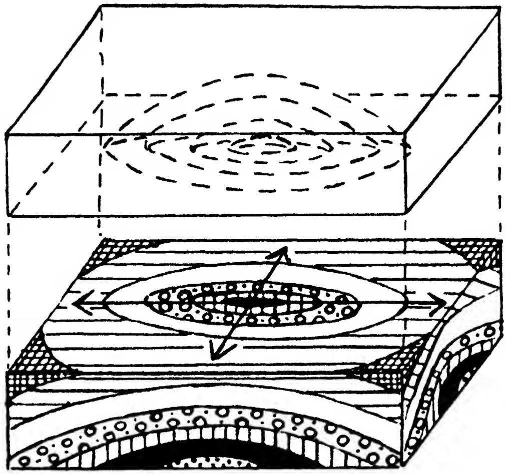


FIG. 21

Exs. (Domes.) Weald of Kent. Quarter-inch, Sheets 20 and 24. Woolhope Inlier. Quarter-inch, Sheet 14, and *Q.J.G.S.*, Vol. LXXXIII, pl. xl.

(Basins.) South Wales Coal Basin. Quarter-inch, Sheets 14 and 18. Forest of Dean Coalfield. Quarter-inch, Sheet 14.

ON THE APPEARANCE OF FOLDS ON CONTOURED MAPS

The strike of any folded bed on a contoured map may be found by the same method as on p. 16, by joining any two points of outcrop at the same altitude. Care must be exercised, however, to see that points of outcrop *on the same side of the axis* are joined. The test of this is whether the strike lines are parallel or not. For instance, in fig. 22 O, P, Q, R are points of outcrop at the same altitude, and it is quite possible to join either OP, QR, or OQ, PR. But,

since OQ is parallel to PR and OP is not parallel to QR, OQ and PR are strike lines and the axis of the fold lies somewhere between OQ and PR. It is, of course, obvious that the fold is an anticline and not a syncline, for the dip in the lower half of the diagram is towards the south, since the outcrop points downstream.

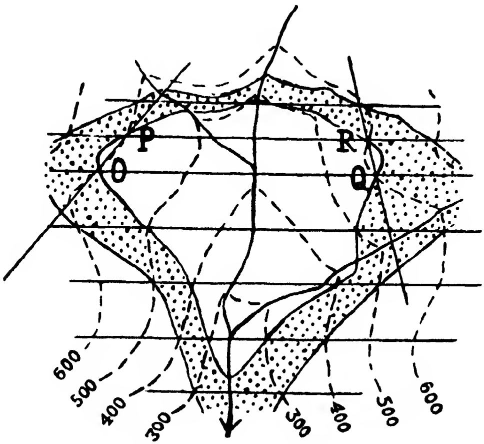


FIG. 22

Note also that the fold is an asymmetrical one, since the strike lines to the south of the axis are a different distance apart from those to the north of the axis. The dip is, in fact, steeper to the north of the axis, where the strike lines are closer together. The wider outcrop also accompanies the flatter dip.

Compare this diagram with that of the simple valley inlier on p. 51.

The problem of plotting the outcrop of a fold, given the position of the axis and the amount and direction of the dip on opposite sides of it, has been discussed by the author elsewhere.[1] The problem of mapping the outcrop of basins, &c.,

---

[1] *Dip and Strike Problems, Mathematically Surveyed*, 1934, p. 13.

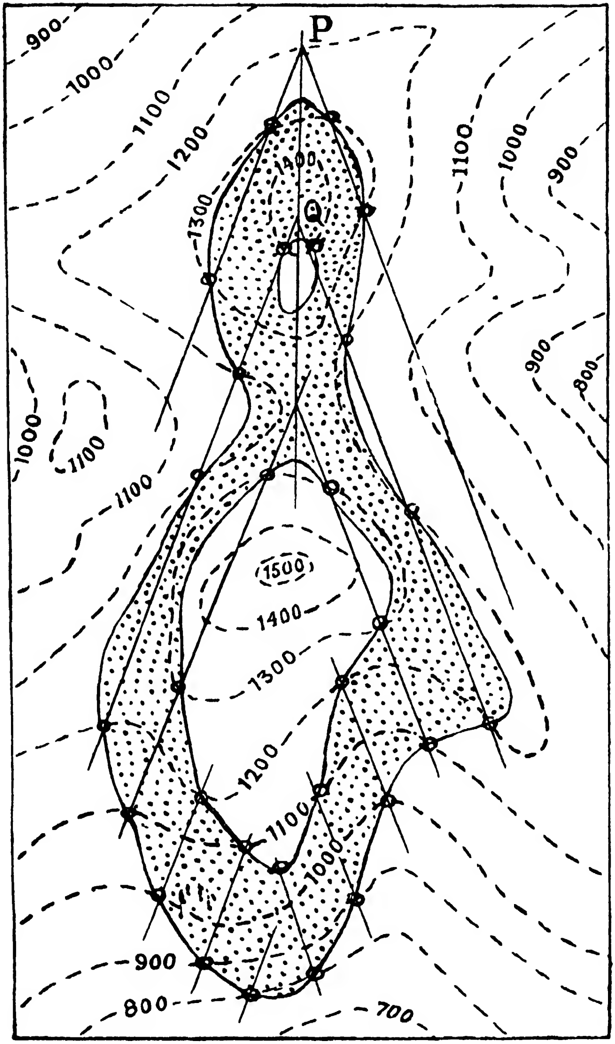

P
Q
900
1000
1100
1200
1300
1400
1100
1000
900
900
800
1000
1100
1100
1500
1400
1300
1200
1100
1000
900
800
700

Fig. 23

from isolated points of varying dip is beyond the scope of the present work, but has been treated of by G. L. Elles.[1]

Additional complication is introduced if the fold pitches, for in this case the strike lines on one side of the axis, though parallel in themselves, will not be parallel to those on the other side.

For instance, in fig. 23, a little experiment will show that the various points of outcrop must be joined up as shown and the structure is revealed as a symmetrical syncline pitching to the south (since the strike lines ' V ' to the north). Any other method of joining up the points of outcrop will give a hopeless confusion of strike lines and reveal no reasonable structure whatever.

The direction of pitch in the above example is PQ, and the amount is 100 ft. in the distance PQ.

[1] *The Study of Geological Maps*, 1921, pp. 26 and 27.

CHAPTER V

ON FAULTS

A FAULT is a dislocation of the strata forming the crust of the earth, due to tension consequent on folding, earthquakes, or isostatic readjustments between the various constituents in the interior.

The surface along which the movement has taken place may be a plane or curved one. For the present purpose we shall ignore the latter and shall consider the movement to have taken place along a plane surface known as the *fault plane*. We shall further exclude such fractures as joints, and consider that the dislocated surfaces remain in contact. The fault plane may have any direction whatsoever, and may have any disposition with regard to the strata it traverses.

The movement along a fault plane may be (1) mainly vertical, (2) mainly horizontal, (3) obliquely to these directions. We shall consider in detail only those movements which are nearly vertical, the fault plane being, of course, itself nearly vertical in this case. Horizontal movements will be briefly discussed on pages 46 and 47, while oblique movements are beyond the scope of the present work.

FEATURES OF FAULTS AS SEEN IN SECTION

Fig. 24 represents a generalized section through strata dislocated by a fault with a steeply inclined fault plane.[1] It is obviously impossible to say absolutely whether the strata on the left-hand side of the fault have moved down, or whether those on the right-hand side have moved up. For purposes of discussion, however, we may say that the left-hand side has moved down relatively to the right-hand side, and is therefore known as the *downthrow* side of the fault

[1] It is, of course, understood that the projecting land surface has been planed down smooth by subsequent denudation, so that no lower elevation of the ground surface is implied on the downthrow than on the upthrow side of the fault.

relatively to the right-hand or *upthrow* side. It should be particularly noticed that after denudation *newer beds are brought against older on the downthrow side of the fault.* It is further to be noted that, apart from localized bending immediately adjacent to the fault plane, a fault *causes no change of dip* in the strata affected.

The angle which the fault plane makes with the *vertical* (viz., the angle F′FT) is known as the *hade* of the fault, the angle it makes with the horizontal (viz., the angle F′FX) the *dip* of the fault, although this latter term is not in general use. Considerable confusion has arisen in the past by authors using the term ‘ hade ’ loosely for the angle made by the fault plane with the horizontal, instead of with the vertical. It may be noted that the hade is usually low in hard strata and higher in soft, and that where the fault traverses hard and soft strata alternately the fault plane may follow a zigzag course. When the fault plane is vertical the hade is zero; when the fault plane is horizontal the hade is 90°.

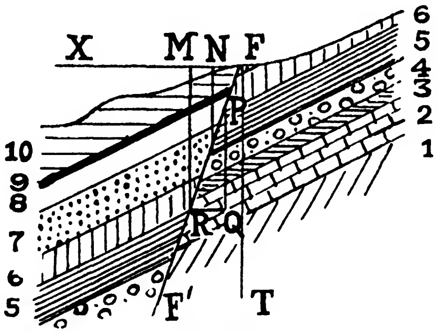


FIG. 24

The vertical distance between the displaced ends of a faulted stratum is known as the *throw* of the fault, while the horizontal distance is known as the *heave*. For instance, in the diagram the junction between beds 5 and 6 is displaced from P on the right-hand side of the fault to R on the left-hand side, through a vertical distance PQ and a horizontal distance RQ. PQ is, therefore, the throw of the fault, RQ

the heave. We shall briefly consider the determination of these factors from the geological map later. If the fault plane is vertical the heave is zero; if the fault plane is horizontal the throw is zero.

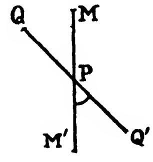
Since every fault must end somewhere it follows that the throw of the fault will vary along its course, and where the fault finally dies out the throw is nil. *Rotational faults* of American authors are faults of this type.

It is usual to divide those faults which show approximately vertical movement into those where the fault outcrop runs in the direction of dip of the strata—*dip faults*—and those where it runs in the direction of strike of the strata—*strike faults*. Figs. 24 and 25 both represent sections through strike faults, since the fault outcrop runs away from the observer in the direction of the strike of the strata.

The effects of the two types of fault on the surface outcrops will be shown in the sequel to be very different. Each type may again be subdivided into *normal* or *gravitational*, and *reversed* or *compressional*.

In fig. 24 the left-hand group of strata may be said to have slipped down the fault plane under gravity. Such a fault is known as a *normal* or *gravitational* fault, and may be recognized in section by the fact that the angle of hade *faces the downthrow side of the fault across the fault plane*—'*hades towards the downthrow*'. In fig. 25, however, the opposite occurs. The faulting in this case may be considered as due to lateral compression, causing the strata to override one another. Such a fault is called a *reversed* or *compressional* fault, and is recognized in the section by the fact that the angle of hade *faces the upthrow side of the fault across the fault plane*—'*hades towards the upthrow*'.[1]

[1] It must be understood that in these definitions we imply the angle of hade whose apex points upwards, viz., the angle M′PQ′ in the diagram, not the angle QPM; otherwise the definition must be reversed.



It is important here to notice the effect of these two types of fault in the vertical borehole. In fig. 24 a shaft sunk at the surface anywhere beyween M, N, will fail to strike stratum 5 at all; for this reason the distance MN is known to the miner as *barren ground.* In fig. 25, however, a shaft sunk anywhere at the surface between M, N, will strike stratum 6 twice. A reversed fault practically always,

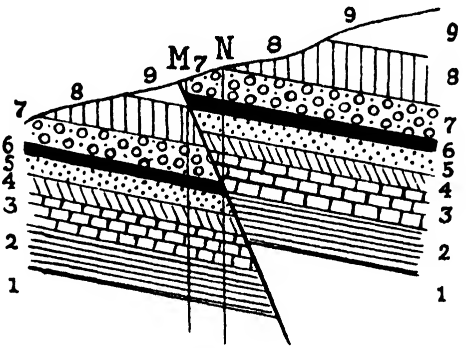


FIG. 25

therefore, causes duplication of the strata *in the vertical borehole,* and for this reason is always a desirable feature in mining operations.

In actual fact the dip in reversed faults is more usually low, so that these more frequently come under the heading of horizontal movements (p. 46). It is probable that the majority of faults are normal. Truly vertical or truly horizontal faults can, of course, be neither normal nor reversed.

FEATURES OF FAULTS AS SEEN IN PLAN

On the published sheets of the Geological Survey surface faults are indicated by white or blue lines, the downthrow side being indicated by a small bar, thus : ——ı——. Of two faults cutting one another the older will show a broken line, having been dislocated by the later one; this will apply both in plan and section. The later fault will often terminate against the earlier one. A fault is newer than any

strata which it displaces, older than any beds which overlie or truncate it.

If the fault plane is vertical its outcrop will be a straight line, whatever the nature of the surface relief, just as in the case of a vertical stratum. If the fault plane is not vertical, it will only crop out in a straight line if the ground surface is flat. In other circumstances it will form a curved line and will follow the trend of hills and valleys, just as a dipping stratum.

We have already suggested dividing faults into those where the fault plane runs in the direction of the dip of the strata—dip faults—and those where the fault plane runs in the direction of the strike—strike faults. The very different effects of the two on the surface outcrops after denudation is shown in three representative cases, illustrated in fig. 26.

In the case of dip faults (fig. 26 *a*) the outcrops are displaced sideways, the amount of displacement depending on the magnitude of the throw, PQ. Various cases arise, owing to the relationship between the dip and the ground slope.[1] If the student draw these for himself, he will be able to deduce the general rule that the outcrops are shifted *in the direction of the dip*—or in the direction of the newer beds—*on the upthrow side of the fault, unless the ground slopes in the same direction as the dip, and at a greater angle*, when the reverse occurs. It is thus always possible to tell which is the downthrow side of the fault, given the dip; or, conversely, given the downthrow side of the fault, it will always be possible to find the direction of dip.

Contrast this rule with the rule about the outcrops tonguing downstream (p. 14).

The case of strike faulting is far more complicated.

In fig. 26 *b*, walking along the surface in the direction of dip, the succession of strata traversed is: 1, 2, 3, 4, 5, 6, 3, 4, 5, 6, 7. The strata are thus repeated. In fig. 26 *c*, however, the order is: 1, 2, 3, 4, 5, 6, 8, 9, 10. Bed 7 is not visible at

[1] These have been discussed and illustrated in the author's *Dip and Strike Problems, Mathematically Surveyed*, 1934.

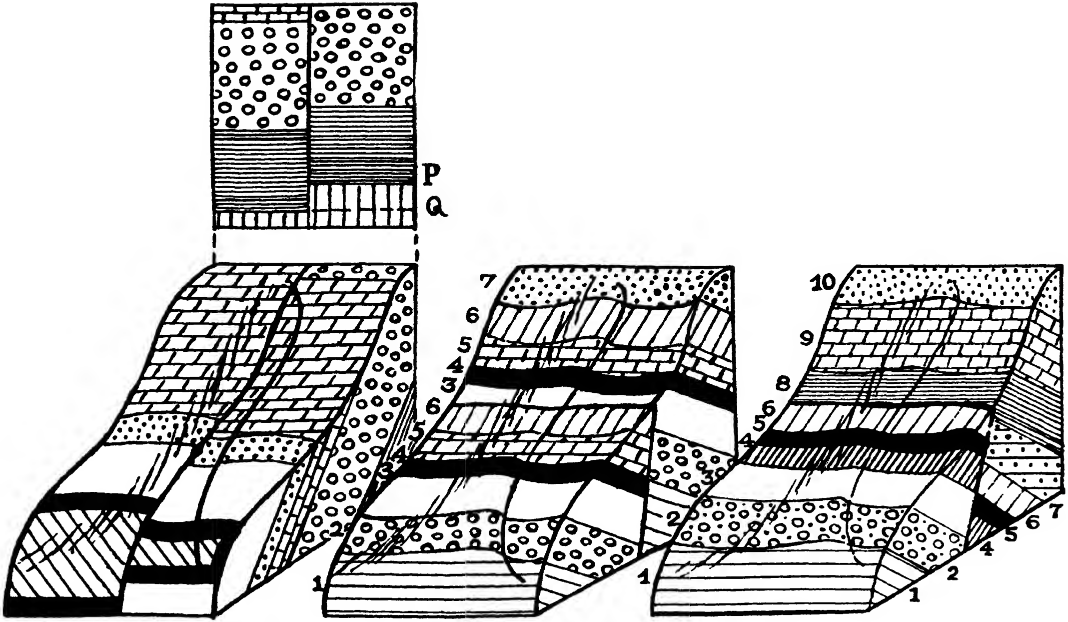


FIG. 26.—Simple Types of Fault

a. Dip Fault, causing Displacement of Outcrops at the Surface. *b.* Normal Strike Fault, causing Repetition of Outcrops at the Surface. *c.* Reversed Strike Fault, causing Beds to be cut out at the Surface.

the surface. It is, in fact, cut out by the fault, and there is no means of telling from surface indications that it exists in the sequence at all. It is clear then that a strike fault will either cause repetition or cutting out of beds at the surface. Which of these will occur, however, depends on the relationship between the dip, the ground slope, and whether the fault is normal or reversed. A very large number of cases occurs, which have been discussed by the author elsewhere.[1] From these we discover that it is not possible to formulate any rule that can be generally useful.

It is, however, always possible to state which is the downthrow side of the fault, for, save in the most exceptional circumstances,[2] the newer beds will always be found on that side of the fault.

It is occasionally possible, from a study of the fault outcrop, to tell whether a fault is normal or reversed. If the ground is flat, the outcrop will be a straight line, whether the fault is normal or reversed. If the ground is undulating, however, the relationship of the fault outcrop to the surface contours may

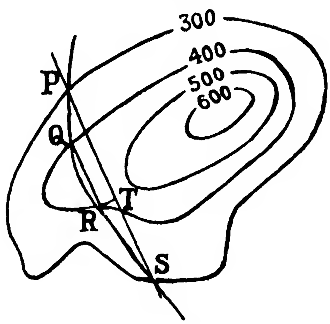


FIG. 27

reveal the nature of the fault. For instance, in fig. 27, PQRS is the curved outcrop of a fault cutting the 300-ft. ground contour in P, S, and the 400-ft. ground contour in Q, R. Along the line QR, therefore, the fault outcrop is at a higher level than along PS. The fault, therefore, slopes or hades in the direction R ⟶ T. The fault plane falls, in fact, 100 ft. in the

---

[1] op. cit. [2] *ibid.*

horizontal distance RT. The amount of the hade is, therefore, $\cot^{-1}\frac{100}{RT}$, which can be found if the horizontal scale of the map is given.

The throw of a *dip* fault can be approximately gauged by comparing the strike lines of any one outcrop on opposite sides of the fault. For instance, if the 500-ft. stratum contour for one side of the fault is the 300-ft. stratum contour for the other side *for the same outcrop*, then the throw of the fault is obviously 200 ft.

FAULTED FOLDS

Since in a dip fault the outcrops are shifted in the direction of the dip on the upthrow side of the fault, it follows that with a dip fault traversing an anticline the outcrops will be displaced outwards in opposite directions on the two limbs of the fold, since they dip in opposite directions. This is usually recognized by saying that the outcrops on the two limbs of an anticline traversed by a dip fault are shifted *nearer together after denudation on the downthrow side of the fault.* The opposite will obviously be true for the syncline.

It is an instructive lesson for the student to draw the two cases for himself.

EXAMPLES OF FAULTS ON GEOLOGICAL MAPS

Amongst examples almost too numerous to quote, the following one-inch survey maps may be specially noticed as showing the displacement of outcrops due to dip faulting and the repetition of outcrops due to strike faulting: Holy I., Sheet 4 (N.S.), Stoke-on-Trent, Sheet 123 (N.S.), Whitehaven, Sheet 28 (N.S.), and the Orkney Is., Scotland, Sheet 119 (N.S.).

Faulted anticlines and synclines are well seen in the Cork map, and in the map accompanying Morris and Fearnsides' paper on the Nantlle Slate Belt (*Q.J.G.S.*, Vol. LXXXII, 1926).

HORIZONTAL MOVEMENTS

Horizontal movement may take place along a plane either mainly horizontal or mainly vertical. Those which take place along a horizontal or nearly horizontal plane are known as *thrusts* or *slides*; by faulting of this character strata may be carried laterally many miles from their place of deposition. Thrusts may be also looked upon as faults with a very high

hade or low dip. Their outcrop on a geological map with undulating relief, instead of approximating to straight lines like those resulting from vertical movements, will present very sinuous outcrops, following the trend of hills and valleys, just as would a stratum with low dip. Such thrusts nearly always crop out in the direction of strike of the strata. By virtue of their mode of origin as a result of horizontal forces, either with or without preliminary folding, thrusts are nearly always reversed in character.

It may not always be easy to distinguish on the map between a thrust and an unconformity. With a thrust, however, older beds may often overlie newer, which can never be the case with a simple unconformity. The faulted nature of the junction may also sometimes be recognized by wisps of rock of different ages being caught up along the fault plane.

Where the movement has taken place along a plane mainly vertical we have the type of fault known as *tears*. Their effect is to displace the surface outcrops, just as is the case with dip faults, since they usually outcrop in the direction of dip. The difference between the displacement of outcrops caused by a tear fault and by an ordinary dip fault is that in the former the outcrops are all displaced *sideways an equal amount*, whatever the dip of the strata. For instance, the outcrop of a vertical dyke will not be affected by a vertical movement, but it will be displaced by a tear fault the same distance as the strata it traverses. The outcrops on opposite limbs of an anticline or syncline, instead of being displaced inwards or outwards, will be displaced sideways the same amount on both sides of the fault plane.

Exs. Thrusts are well seen in the map of the Assynt District, Scotland, one-inch, parts of Sheets 101, 102, 107, 108. Ambleside, Sheet 98 NW. (O.S.), shows two good tear faults running NNE. from Esthwaite Water and Coniston; Coniston Water may, in fact, owe its existence to the line of weakness caused by the fault. Some of the faulting in the Vale of Clwyd (N. Wales, Sheet 108 (N.S.)) is also considered to be of this type.

SPECIAL TYPES OF FAULT

Step Faults

Step faults consist of a sequence of faults, all downthrown in the same direction. This will be seen in section by the strata descending in a succession of steps, or in plan by the frequent repetition of the sequence at the surface

(strike faults), or the repeated displacement of the outcrops in the same direction (dip faults).

Trough Faults

Trough faults consist of two more or less parallel faults, both downthrown on their inner margins (fig. 28). The block between the two faults has thus collapsed, giving rise on the subsequent denudation of the surrounding country to a *graben* or *rift valley*. Such faults may obviously run

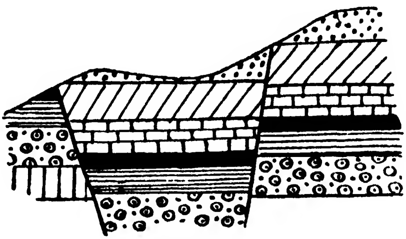


FIG. 28

either in the direction of the dip or the strike of the strata. The Great Rift Valley of Africa and the Rhine Valley are foreign examples of such structure; the Vale of Clwyd (N. Wales, Sheet 108 (N.S.)) is a good British example.

The opposite to a graben, where the central block has moved upwards instead of downwards relative to the two outer blocks, is known as a *horst block*.

Imbricate Structure. This consists of a rapid succession of reversed faults with low hade, developed over a small area. This type of structure is seen in the NW. Highlands of Scotland.

Cauldron Subsidence. This is a circular fault along which a portion of the earth's crust is supposed to have collapsed bodily into the interior. Glen Coe, in the neighbourhood of Ben Nevis, is the type example.

CHAPTER VI

ON THE FORMATION OF INLIERS AND OUTLIERS

AN *inlier* on a geological map consists of an area of *older rocks entirely surrounded by newer.* An *outlier* is exactly the reverse, consisting of an area of *newer rocks entirely surrounded by older.* As they may be formed in a variety of different ways, it seems convenient to summarize their various modes of origin in a separate chapter.

They may, in fact, be formed in the following ways:

(1) BY THE DENUDATION OF CONSTANTLY DIPPING STRATA

(*a*) The simplest case of this is that exemplified by undulating relief on horizontal strata. As we have seen on p. 14, the outcrops of horizontal strata follow the ground contours. The newest strata will, therefore, be exposed as islands on the tops of hills, the oldest as islands in the hollows of depressions.

In the simplest case, then, outliers will occur as horizontally bedded areas of rock on the summits of hills, inliers at the bottoms of depressions. A common example of outliers of this type is shown in the patches of strata detached from the main escarpments by denudation.

Exs. Ingleborough. Sheet 97 SW. (O.S.). The Ingleborough Grit forms outliers at the tops of hills and the lowest beds of the Carboniferous Limestone series inliers in the valley bottoms.

Sidmouth. Sheets 326 and 340 (N.S.).

Sheet 15 of the quarter-inch map shows outliers of Lias, Inferior Oolite and Lower Greensand detached by denudation from their main escarpments.

(*b*) Another case is where the strata dip down the valley, towards its mouth. At the upper end of the valley, where the slope is steep, the outcrops tongue up the valley, since the slope of the ground is steeper than the dip. At the lower end, where the valley is flatter, however, the dip is steeper than the slope of the valley; consequently the outcrops tongue down the valley and we get inliers in the intermediate part of the valley (fig. 29).

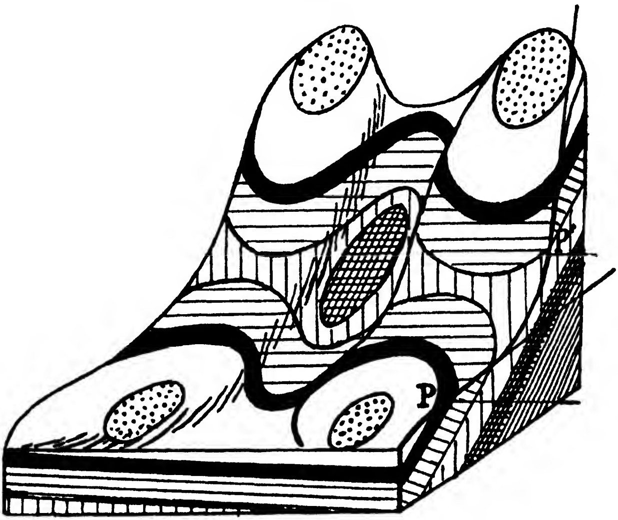


FIG. 29

The appearance of such an inlier on the contoured map is shown in fig. 30.

Note particularly the difference between this diagram and that of the anticline on page 36. Here the strike lines *increase* in value continuously towards the north of the map; there they *decrease* in value after the axis is crossed. Furthermore, since the dip remains constant the strike lines are the same distance apart throughout.

Such a structure will also lead to the development of outliers on the ridges (fig. 31).

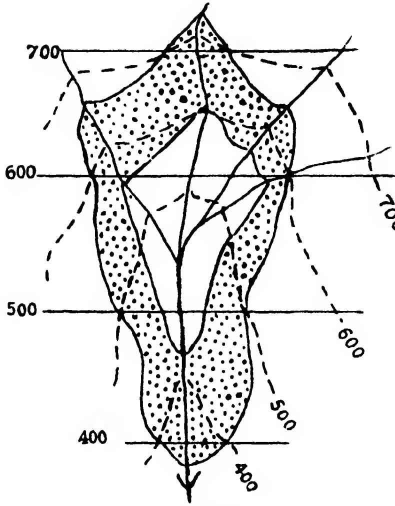


FIG. 30

Ex. Inliers of this type are well seen in the Cleveland district

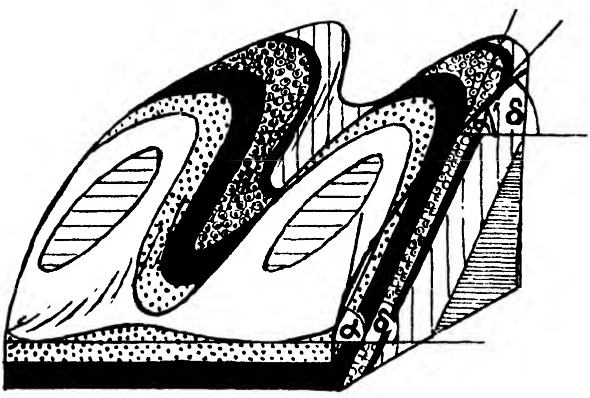


FIG. 31

of Yorkshire (Egton, Sheet 43 (N.S.)), where the elliptical-shaped inliers of Lias, north and south of the watershed, are

the result of denudation in valleys with changing slope. The structure here, however, is slightly accentuated by folding.

(2) BY THE DENUDATION OF AN ANTICLINE OR DOME

The denudation of an anticline or a dome, in a valley, whether striking longitudinally or transversely, or of a dome on level ground, will give rise to an inlier (figs. 18, 21 and 22).

By an analogous process the denudation of a syncline or basin will give rise to an outlier (fig. 18).

Exs. Weald of Kent. Quarter-inch, Sheets 20 and 24. The lowest Cretaceous strata form an inlier in the centre, surrounded by successively newer and newer strata, dipping away from the centre in all directions. The English Channel cuts diagonally through the inlier.

The S. Wales Coal Basin. Quarter-inch, Sheets 14 and 18. The Coal Measures in the centre are entirely surrounded by the underlying Lower Carboniferous and Devonian, which dip towards the centre of the basin.

(3) AS A RESULT OF UNCONFORMITY

(*a*) *By Complete Submergence*

In fig. 32 the lower series dips downstream at a greater

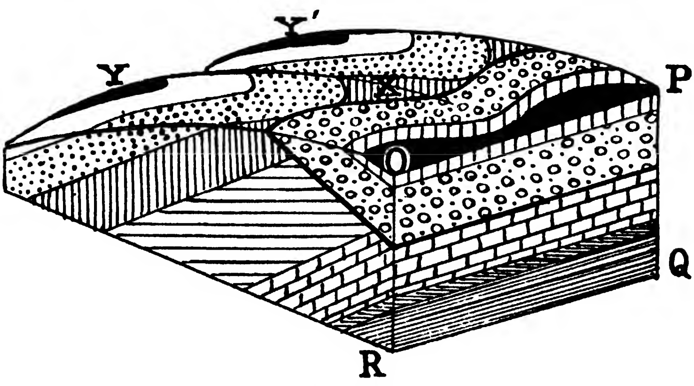


FIG. 32

angle than the valley floor; therefore the beds tongue downstream. The upper series dips in the opposite direction and

therefore the beds tongue upstream. The net result is an inlier at the point X. Outliers will tend to be formed on the ridges, as at Y, Y′.

The appearance of such an inlier on a contoured map is pictured in fig. 33.

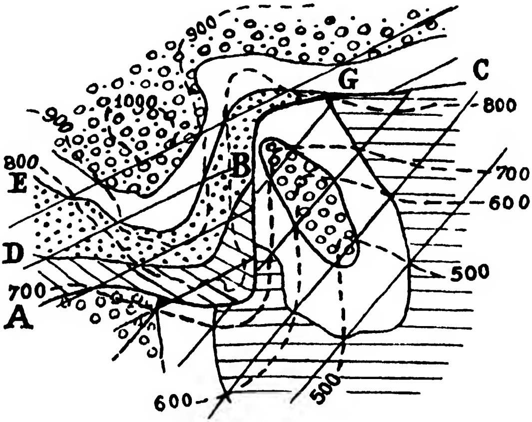


FIG. 33

(b) By Incomplete Submergence

If the second set of strata is deposited round a pre-existing land mass which has been incompletely submerged, subsequent denudation will give rise to an inlier (fig. 34). In

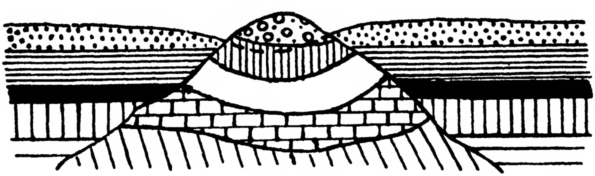


FIG. 34

this case the inlier will be entirely surrounded by members of the newer series, and not only on one side, as is the case in figs 32 and 33.

Ex. The English Lake District is almost entirely surrounded by the Carboniferous Limestone. It is probable that the highest zones were deposited unconformably right over the Lower Palaeozoic rocks, and that the present structure is due to the denudation of the dome; the lowest zones of the Carboniferous, however, were probably never deposited over the centre of the area.

(4) AS A RESULT OF FAULTING

In the diagram (fig. 35) the front half of the model has been thrown down by a strike fault, giving rise to an inlier in the valley at the point N. In a similar way faulted outliers will tend to be formed on the ridges, as at M, M′ in the figure.

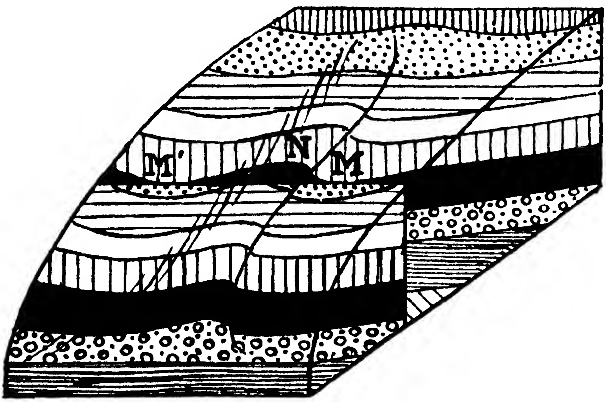


FIG. 35

Exs. Examples of this type of inlier are almost too numerous to mention, but particularly good ones are seen where the lowest zones of the Carboniferous Limestone series or the Lower Palaeozoics are truncated by the Dent or Craven faults.

Ingleborough. Sheet 97 NW. (O.S.). Also the Survey Guide to the Ingleborough Model and the maps accompanying the following papers; E. J. Garwood and E. Goodyear, 'The Lower Carboniferous Succession in the Settle district, &c.', *Q.J.G.S.*, Vol. LXXX, pl. xx; A. A. Miller and J. Selwyn Turner, 'The Lower Carboniferous Succession along the Dent Fault, &c.',

Proc. Geol. Assoc., Vol. XLII, pl. i; J. Selwyn Turner, 'The Lower Carboniferous Succession of the Westmorland Pennines', *Proc. Geol. Assoc.*, Vol. XXXVIII, pl. xi.

A pitching fold traversed by a dip fault will produce the same result.

Very special types of faulted inliers and outliers are afforded by the *klippen* and *windows* in an overthrust mass. *Klippen* are detached outliers, bounded *below* by a thrust plane, along which the constituent mass has been moved often for an enormous distance from its place of origin. *Windows*, on the other hand, are inliers exposed by denudation through an *overlying* thrust plane. Excellent examples of these are to be met with in the Swiss Alps, but will not be seen by the student on British geological maps.

CHAPTER VII

ON IGNEOUS AND METAMORPHIC ROCKS

IGNEOUS ROCKS

IGNEOUS rocks are divided into three types: *plutonic*, *hypabyssal* and *volcanic*.

The *plutonic* rocks are those which have been *intruded* through the previously formed sediments, having been consolidated under the pressure of the superincumbent strata and exposed by subsequent denudation. They tend, therefore, to form irregular-shaped bodies, known as *stocks* and *bosses*. Some plutonic rocks, such as granites, often cover areas of many square miles in extent.

Occasionally in folded strata the igneous body takes on the outline of the folds invaded, so that the strata dip away from them in all directions. Of these the *laccolith* (*laccolite*) and *batholith* (*batholite*) may be regarded as the cause of the folding, whereas the *phacolith* (*phacolite*) is to be regarded as the result of the folding, for it occupies the lenticular space at the crests of anticlines and depths of synclines.

The *hypabyssal* rocks are a peculiar type of igneous rocks, characterized by their relatively small thickness but considerable lateral extent. They are dependent for their existence on lines of weakness in the invaded strata and have been intruded either more or less vertically along the joints or laterally along the bedding planes. The two types are known respectively as *dykes* and *sills* (fig. 36). Dykes are often the accompaniment of plütonic activity and may frequently be seen radiating outwards from a plutonic boss (fig. 37). Sills, in addition to being intruded along the bedding planes, have often broken through from one bedding plane to another.

The *volcanic* rocks or lavas differ from the previously

mentioned rocks in that they have been poured out and consolidated *at the surface* (sometimes the sea floor), instead of underground. Each flow of lava, therefore, will be spread over the surface of the pre-existing strata, and will be

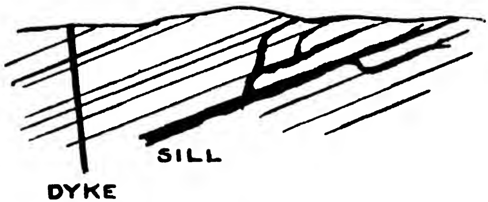


Fig. 36

covered by subsequent sedimentation, and so on. The result will be that, instead of occupying shapeless areas unrelated to the previously consolidated sediments, they will occur *interbedded* with them, as if they were part of the stratified sequence.

Volcanic Necks are the chimneys or vents of extinct volcanoes, which have become choked up with volcanic agglomerate, tuff and lava.

Ring Dykes form a special type of dyke which occurs in concentric fashion round cauldron subsidences; they represent the consolidated infillings of ring fractures, developed round more or less well-defined centres.

Cone Sheets. These are similar structures which are more or less steeply inclined in the shape of a cone towards a common centre underground.

In the index of strata on any geological map the intrusive (plutonic and hypabyssal) rocks are placed in a separate column, generally below and detached from the column of strata. Their age, if known, is stated at the margin. The lavas, on the other hand, being interstratified and contemporaneous with the sediments in which they occur, will be placed in their proper position in the column of strata; they will be noted as lavas in the margin.

METAMORPHIC ROCKS

These are *foliated* rocks, intimately related to the igneous intrusions. They will generally occupy belts round or adjacent to the igneous bodies, and in the case of plutonic intrusion the *metamorphic aureole* may extend radially for several miles from the margin of the boss. If they were originally stratified rocks their dip may be preserved, and they may have a subsequent pseudodip, known as the *direction of foliation*, impressed on them.

It is obvious that, whereas the intrusive rocks are liable to alter all the rocks invaded, lavas can only metamorphose the strata lying immediately *below* them, as those above them were not in existence at the time of their extrusion. This fact often affords a valuable field criterion for distinguishing between sills and true lavas.

THE APPEARANCE OF IGNEOUS AND METAMORPHIC ROCKS ON THE GEOLOGICAL MAP

On the geological map plutonic bosses will generally form irregular-shaped bodies, but approximating to the

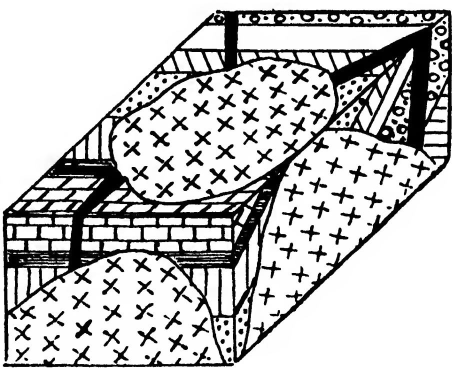


FIG. 37

circular, whose boundaries will run quite independently of the outcrops of the stratified rocks. They are shown in plan and section in fig. 37.

Exs. Cheviot. Sheets 3, 5, 6 (N.S).

Penzance. Sheets 351 and 358 (N.S.). The sea margin is evidently the approximate boundary of the granite.

Arran. Scotland, Special Sheet.

Laccoliths generally approximate to the circular in ground plan, though they may be elongated in the direction of strike. The quaquaversal dip, if present, will serve to distinguish them from batholiths. Apart from their generally smaller size it will often be impossible to separate them from bosses on the map evidence.

Ex. Corndon Hill, Salop. Sheet 60 SE. (O.S.).

Dykes, being thin and approximately vertical-sided bodies, will run in straight, narrow lines across the map, irrespective of the outcrops of the sedimentary strata. They will often radiate from a plutonic mass, and may extend for many miles.

Exs. Rothbury. Sheet 9 (N.S.).

Penzance. Sheets 351 and 358 (N.S.).

Skye. Scotland, Sheets 70 and 71, and neighbouring areas.

Sills, being intruded along the bedding planes, will follow the outcrops of the sedimentary strata. On the map they may sometimes be distinguished from interbedded lavas by the fact that they break through bedding planes, to appear at lower or higher horizons in the stratified sequence.

Exs. Sills are splendidly displayed in the Holy I. Sheet, No. 4 (N.S.). Note how the Whin Sill shifts its horizon in the Carboniferous sequence. Also Alnwick, Sheet 6 (N.S.).

Lavas are seen in the Old Series maps of the Snowdon district and of the Lake District.

Volcanic Necks are seen in the Oswestry sheet, No. 137 (N.S.), and in that of E. Fife, Scotland, Sheet 41 (O.S.), and Arran. Note their circular shape, but of a size much inferior to that of bosses.

Ring Dykes and Cone Sheets are to be seen in the Ardnamurchan Sheet, Scotland, Sheets 51 and 52 (N.S.), and in Mull, Sheet 44 (N.S.).

Metamorphic rocks, if originally sedimentary, may have their original dip preserved. This will be indicated in the usual way, while the direction of the foliation will be indicated by an arrow of a special type. If the metamorphism has been caused by an igneous intrusion, a metamorphic aureole may be indicated.

Exs. Penzance, Sheets 351 and 358 (N.S.). The metamorphic aureole extends two miles into the adjacent Lower Palaeozoic beds and greenstone.

Teignmouth. Sheet 339 (N.S.).

Scotland. Sheets 4, 5, 8, 9 (N.S.).

THE AGE OF IGNEOUS ROCKS, AS DETERMINED FROM THE GEOLOGICAL MAP

Igneous rocks will be, in general, newer than any beds they traverse, older than any beds they underlie. For instance, in fig. 37 the intrusion of the igneous material is the latest phenomenon displayed. The tilting of the strata was probably earlier than the intrusion. Dykes and sills will often be displaced by faults and this factor may afford a clue to the age of the intrusion.

If igneous intrusions pass under unconformable beds, they are obviously earlier in age than the deposition of the unconformable beds. It is not possible to tell their age unless they are seen in actual contact with the unconformable series or are connected with them by faulting.

Igneous intrusions are obviously subsequent to any rocks that are metamorphosed by them.

Exs. Penzance. Sheets 351 and 358 (N.S.). Note that the igneous rocks are not placed in their historical order in the index to strata; the greenstone is evidently earlier in age than the granite, since it is metamorphosed by it.

See also the descriptions of the Teignmouth and Holy I. Sheets on pages 91 and 83.

CHAPTER VIII

ON GEOLOGICAL MAP READING AND SECTION DRAWING

In reading any geological map there are three factors to consider: the surface relief, the order of superposition of the strata, and the direction of dip. Unless two, at least, of these factors are known, we cannot accurately determine the structure of the district. In problem maps generally only two of these factors are given, viz., the first and second, and the student is left to determine the third. But the information given on most of the New Series maps of the Geological Survey is so complete that little is left to the imagination of the student.

It should be quite possible to obtain a picture of the geological history and structure of the district from a study of the map alone, and this should be further elucidated by the drawing of sections in suitable directions across the area under discussion. The mistake that students almost invariably make is in determining the structure of the district from the section itself, instead of using the section to confirm and illustrate the structure which has been previously elucidated from the map itself.

The best way to undertake the description of a geological map is to describe the events leading up to the present distribution of strata in chronological order, stating at each point the reasons for one's interpretation, and calling attention to any feature illustrating or consequent on the events described. The description will thus take on the nature of a story, rather than a mere collection of unrelated facts. It should always conclude with a brief discussion of the influences of the geological structure on the topography of the area, coast erosion, &c., together with reference to any

obvious economic products or mineral deposits, and their location as a factor in the distribution of the population within the area.

The map descriptions given on pages 71 to 92 will illustrate the principle aimed at.

The object of drawing a geological section across the map is to obtain the most reliable picture of the superposition of the strata as they would appear if the country were cut through by a knife in a vertical direction and viewed edgeways.[1]

It is obvious, therefore, that the section should be drawn as nearly as possible in the direction of dip, so as to combine the maximum variety of rock structure with the maximum of topography.

Further, it should be drawn, as nearly as possible, to true or 'natural' scale, i.e., the scale of feet in the vertical direction should be the same as in the horizontal. If this can be effected we shall have a section in which the hill slopes are true to life and not unscaleable precipices, and in which the strata can be viewed with dips and thicknesses which are accurately related to one another. Owing, however, to the fact that the length of the section generally far exceeds the height, this is not always practicable.

To take an example, if the horizontal scale is one inch to a mile (5280 ft.), and the ground surface nowhere exceeds 1000 ft., a true scale section will give us a contour outline with a maximum height of $\frac{1}{5}$ inch. Obviously no great detail of geological structure can be filled in on such a section, and in such a case it is necessary considerably to exaggerate the vertical scale,[2] unless one is to be content with a purely diagrammatic section, showing only the broadest structural features of the area. Other difficulties

[1] For some obscure reason such a section is called by the officers of the Geological Survey a *horizontal section*, a *vertical section* consisting of a section, generally on a much enlarged scale, of the strata as seen in a borehole.

[2] In the published sections of the Geological Survey the vertical scale is generally exaggerated three times.

encountered if the scale is exaggerated will be referred to on page 65.

In any case both horizontal and vertical scales should be stated.

Having decided on a suitable scale, the next thing to do is to construct a contour outline, and the accuracy of this will depend on the amount of information as to heights obtainable. In the Old Series maps of the Geological Survey the heights are only indicated by hill shading, with occasional 'spot heights' on the crests of hills, main roads, &c. The more modern (New Series) maps are, however, completely contoured at intervals of 100 ft. below the 1000-ft. line (and 250 ft. above that line), so that the consecutive contours can be marked off along a strip of paper laid along the line of the section.

The base line of the section will, in general, be sea-level. Even if the whole surface of the section lies above (say) the 500-ft. contour, the lower part of the section will be found useful for filling in the geological structure, so as to emphasize the continuity of the folding, &c. Under exceptional circumstances the base line may be taken above sea-level, in which case the fact should be noted in the scale at the margin of the section.

By transferring the strip of paper to the base line of the section and erecting at the various points perpendiculars equal to the relevant heights on our predetermined scale, we can obtain a true outline of the surface of the country. The work will be still clearer if small depressions are made in the contour outline to denote the rivers, and if place names are inserted above the surface of the ground. Compass points should be added at the ends of the section, as well as at any intermediate points, if the section is not drawn along one straight line.

Before proceeding to fill in the geological details the student must make himself acquainted with all the conventional signs relating to dips, &c., used on geological maps, and with the columnar method of tabulating strata. It is particularly to be noted that in all such tables the newest

beds are placed at the top of the column, the oldest at the bottom.

We now proceed to lay another strip of paper along the line of section on the map and mark off the outcrops of the various strata, together with any information as to dips, faults, &c. It is often convenient to number the various strata in the index from the base (oldest) upwards, and to number the beds along the section to correspond with them (fig. 88).

We are now in a position to transfer this record to our contour outline. This is done by marking off the various data along the base line of the section, and projecting them up vertically to cut the contour outline.[1]

We have seen on page 40 that faulting, though it is responsible for the displacement of the surface outcrops, does not affect the dip of the adjacent strata. It is the most satisfactory plan, therefore, to insert now all faults which reach the surface along the line of section, and to make the various strata abut against them. It will thus be obvious from the section which is the downthrow side of the fault, for newer beds will be brought against older on that side.

Since it is not generally possible to tell which way a fault hades, i.e., whether it is normal or reversed, it is convenient to insert faults in the section as almost vertical lines from the surface of the country downwards. If they do not reach the surface along the line of section but are concealed by unconformable beds, their approximate position may be indicated in the beds below the plane of the unconformity. The relative ages of contiguous faults may be indicated, if known, by making them hade towards each other, the newer fault displacing the older in the lower part of the section.

The various faults having been inserted as accurately as

[1] If the map is a manuscript one and not a library copy, and the line of section is in the direction of one of the edges of the map, the detachable strip of paper can be dispensed with, and the section drawn on the same sheet of paper as the map, by projecting contour points and outcrops direct. This method cannot, however, be used if the line of section is oblique to the edges of the map.

possible, the strata should now be added. These should be indicated at each point of outcrop dipping, as far as possible, at the angle stated on the map. As the section will seldom be in the direction of full dip, but at an angle to it, a certain amount of compromise will almost always be necessary in estimating the dip. If no dip marks are available along the line of section we can see from the table of strata whether the beds are in their correct order and conformable, and, if so, no deviation need be made from the dip prevailing in under- or overlying beds where the dip is known. It is also permissible to deduce the dip at any point from that given in the same bed in the direction of strike (at right angles to the line of section), provided the point is not too far off the line of section.

Much information may also be obtained as to the dip of the strata by searching for outcrops which tongue down the valleys, since these always indicate that the dip is towards the mouth of the river (p. 14). Remember also that this is the only case where the strata are inverted, i.e., where the newer strata are farther down the valley than the older.

The superficial deposits should not be inserted at this point.

Considerable difficulties of technique may be encountered at this stage in drawing sections which are not to true scale. For instance, in fig. 39, suppose the true slope of the ground is represented by the line CD, yet owing to the exaggeration of the scale it appears as AB. It is necessary to insert at P_3, P_4, a stratum dipping 20° to the right. This

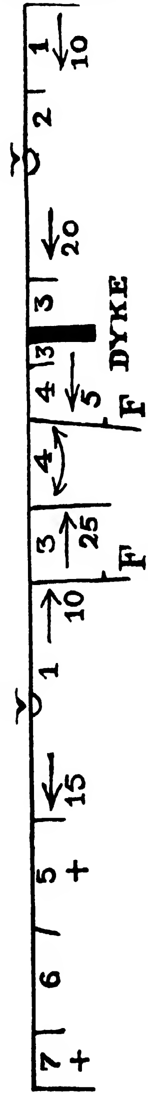


Fig. 38

is obviously impossible, since it would fall entirely outside the surface of the country, whereas in the true scale section the stratum can be inserted quite accurately at P_1, P_2. The only way this difficulty can be overcome is by exaggerating the dip—in this case up to nearly three times—in order to set the bedding plane inside the surface of the country. Not only does this necessitate exaggerating the dip but, as will be seen from the diagram, the thickness must be exaggerated as well, so that an entirely abnormal view of the geological structure is thus obtained.

Anticlines and synclines are generally indicated on the

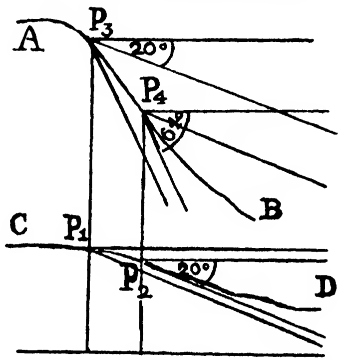


FIG. 39

map by change of dip or by repetition of strata. The repetition of strata must never be assumed as due to faulting unless there is definite indication of such faulting.

It must also be clearly understood that dips shown on the map are those at the point of outcrop only. The presence or absence of folding will indicate how far such dips should be continued underground, the object being, as far as possible, to preserve the individual strata of a constant thickness throughout the fold.

Where there is extensive folding it often renders the structure clearer if the connecting parts of the folds are indicated above the surface of the ground by dotted lines, and below the surface by continuous ones. If the section is

across very low-lying ground, it will sometimes be necessary to continue the strata below sea-level, to indicate the continuity of the folds, but it is not wise to fill up the section with imaginary strata lower in the series, unless there is evidence of their existence in other parts of the map.

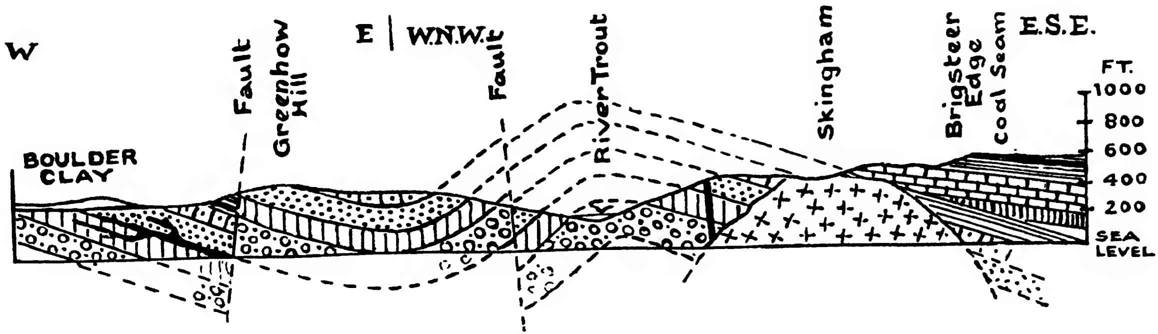
Unconformities, even in the absence of indicated discordance of dip, will generally be readily recognized by the transgression of the outcrops of the unconformable series across those of the lower series. They will, further, generally be recognized by a gap in the index of strata. Such unconformable beds must always be indicated in the section by a marked change in dip (unless the section is drawn along the strike of both series), while the lower series of beds should be continued in section below the unconformable junction.

Dykes, generally displayed as running in straight lines across the map, should be indicated as nearly vertical beds with parallel walls, cutting through the older strata, i.e., the older strata should be continued on both sides of the dyke and not terminate against it. Sills should be inserted as intrusions running more or less parallel to the bedding planes, and occasionally breaking through into a contiguous stratum. Bosses will be indicated as irregular-shaped masses, intruded through the strata, and should be continued in the section below the strata they have invaded.

Superficial deposits, such as a boulder clay and river alluvium, should be inserted last as a mere skimming over the solid rocks.

On the maps of the Geological Survey definite and distinctive colours are used for strata of different ages and for igneous rocks of various kinds. These should be reproduced as nearly as possible in the finished section, or if the map is reproduced in black and white, the individual strata should be shaded to correspond with the original map, the essential thing being to render the strata distinct from one another, and as quickly as possible comparable with those of the original map.

A hypothetical section displaying many of the points discussed in the foregoing pages is illustrated in fig. 40.



Vertical Scale Exaggerated Twice

FIG. 40

VERTICAL SECTIONS

The vertical section through the strata at any given point of a geological map is obviously the picture of the strata as they would appear in a borehole or mine shaft, and is therefore of the utmost importance to the mining geologist.

It is clear that, if a natural scale horizontal section has been drawn, the vertical section at any point along that line will be immediately accessible. It will show not only the vertical succession of strata but the relative thicknesses thereof, as well as any unconformities and faults that occur in the succession. If the section is not drawn to natural scale, however, not only will the relative thicknesses be incorrect, but the section may even reveal an incomplete succession.

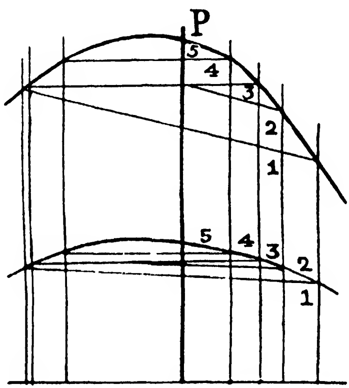


Fig. 41

For instance, in the upper part of fig. 41 the vertical scale has been exaggerated, thereby necessitating an exaggerated dip in the series below the plane of the unconformity. As a result the borehole P does not pass through bed 3 at all. Whereas in the lower part of the figure, which is drawn to natural scale, the bore is clearly seen to pass through a considerable thickness of the bed.

In vertical sections for mining geologists the scale is often greatly exaggerated. For instance, whereas the published horizontal sections of the Geological Survey, apart from those actually drawn on the margins of the one-inch maps, are drawn on a true scale of six inches to a mile, or 880 ft. to one inch, the vertical sections accompanying them are drawn on the

scale of 40 ft. to one inch, an exaggeration of 22 times. The thicknesses of all coal seams and the strata with which they are associated may thus be indicated in great detail.

The diameter of the borehole being small, it is clear that the dip is a matter of little importance in such sections; but any unconformities recognized in the horizontal section may be indicated as inclined or broken lines between the adjacent strata.

CHAPTER IX

DESCRIPTIONS OF REPRESENTATIVE PUBLISHED GEOLOGICAL MAPS

MAP OF THE CHARMOUTH DISTRICT, ACCOMPANYING THE PAPER BY W. D. LANG IN *PROC. GEOL. ASSOC.*, VOL. XLIII, 1932

THE area shown represents large-scale mapping in the Charmouth district. It is particularly instructive for elementary students as, in the absence of dip marks, the structure of the district must be deduced entirely from the sequence of strata and the direction of the outcrops.

The area is drained by the River Char which, with its accompanying tributaries from the Vale of Marshwood, flows in an approximately NE.–SW. direction, to be joined in Charmouth village by tributaries flowing down from the direction of Wootton Fitzpaine.

A preliminary study of the contours and of the index to strata shows that the general principle that where there is no important folding the oldest beds tend to occupy the valleys and the newest beds the hills, is true in this case.

The Vale of Marshwood itself forms a completely closed structure, with the centre of the valley occupied by the oldest beds and succeeded by newer and newer beds as we reach the higher ground. It therefore represents an inlier due to denudation of a dome, so that the dip is everywhere outwards from the centre. Smaller inliers of Black Marls are revealed by denudation in the river-bed itself near Prime Farm. The comparative steepness of the dip is shown by the outcrops pointing downstream near exposures S 18, S 22, E 20.

Erosion in the Wootton Fitzpaine valley has produced what the author describes as a hand-shaped structure, showing four fingers and a thumb. It is probable that most of the

geological outcrops are determined by this river erosion, rather than by marked folding, since they follow the ground contours fairly closely. The Wootton Fitzpaine gap and the Charmouth corridor, however, indicate anticlinal structure, but erosion has not proceeded so far as in the Vale of Marshwood, for only in the immediate neighbourhood of Charmouth and at Thorn Dairy do the lowest beds crop out at the surface. At the latter locality denudation has revealed a small inlier, while the core of the Char Valley anticline is seen on the foreshore at Lyme Regis, where the oldest rocks of all—Middle Blue Lias—form a small inlier surrounded by Upper Blue Lias and aligned in the direction of the axis of the anticline. *Note* that in every one of the tributary valleys the outcrops point upstream.

Note that many of the beds appear to thin out and completely disappear in the sea cliffs to the east and west of Charmouth. This is not due to unconformity, as might be supposed, but simply owing to the steepness of the sea cliffs. According to the principle enunciated on page 15, the steepness of the ground surface determines the width of outcrop; if the cliff is vertical, it is obviously just as impossible to indicate the respective outcrops as it would be individual ground contours. In the neighbourhood of Marshwood village there is, however, thinning out of the Ammonite beds, which cannot be explained as due to surface relief. This gives rise to a small local unconformity—or more properly non-sequence—between the Belemnite Marls and the Middle Lias.

After the erosion of the folded Jurassic beds, the Cretaceous were laid down unconformably across their edges over the whole area of the map. The unconformable nature of the junction is best seen on Wootton Hill, where the outcrop of the Cretaceous transgresses the Middle Lias (coloured yellow), to rest on the Ammonite beds (brown). *Note* that there is no unconformity at the base of the Middle Lias as well. To the west of Charmouth itself the Cretaceous transgress across the Ammonite beds to rest on the lower part of the Belemnite Marls. A study of the relationship

of the outcrop of the Cretaceous to the ground contours shows that the dip is slightly towards the south. (North of Bettiscombe the Cretaceous crop out at 700 ft., and gradually fall to 300 ft. along the sea coast.) So that the final movement in the area has been a slight tilt to seaward.

Subsequent denudation has reduced the Cretaceous strata to outliers in the south-east part of the map.

The important faults are six in number; two of these are dip faults, four strike faults.

The chief dip fault runs in a north-west and south-east direction from Wootton Fitzpaine to the extreme south-east corner of the map. The other runs parallel to it through Charmouth itself and is shifted at Charmouth Mead by one of the strike faults; the latter is, therefore, probably later in age than the dip fault. From the manner in which the dip faults terminate against the outcrop of the Cretaceous, we may infer that they are post-Middle Lias and pre-Cretaceous in age.

The lower part of the Char valley affords a very good example of a faulted anticline. The outcrops of the Ammonite beds to the north of the fault are nearer together than those to the south of the fault, whence we may infer that the fault is downthrown to the north. The other dip fault is also downthrown to the north (or east), as newer beds will always be found on the east side abutting against older on the west. *Note* the displacement of the outcrops immediately north-west of Charmouth (exposures M 7, S 25). Near Penn (exposure S 29) this fault gives rise to a small faulted inlier.

The strike faults run at right angles to these two main faults. Their effect on the surface outcrops is not very clear and they are not seen in relationship to the Cretaceous strata.

The geology has not impressed itself very markedly on the drainage of the area. But it is noticeable how the Marsh Brook and the Middle Brook cling to definite horizons on the east side of the Vale of Marshwood; this is probably due to

small lithological variations, rendering those horizons especially liable to denudation.

The coast erosion is not particularly instructive.

ONE-INCH SURVEY MAPS (N.S.)

ISLE OF WIGHT

Parts of Sheets 330, 331, 344, 345 (*Drift*)

Topographically, the Isle of Wight is diamond-shaped and has its longest axis running in an east and west direction. It is divided roughly in half by a ridge of high ground occupied by the Chalk escarpment. The northern half of the island consists of a low-lying area occupied by the Tertiary beds, while the southern half, occupied by the Cretaceous beds, reveals a central plain, rising to downs 800 ft. high behind Ventnor. These downs form the chief watershed of the island, all the more important streams draining northwards.

The marginal index to the solid strata in this case is drawn to scale, each individual bed being characterized by a special letter. The succession is a continuous one and there are no unconformities. The superficial strata, which should normally be placed above the solid strata, but for convenience have been inset in the corner of the map, are also characterized by distinguishing symbols, but are not drawn to scale.

The newest beds on the map—the Hamstead beds of the Oligocene series—occupy a large tract north of Newport, while the underlying Bembridge, Headon and Osborne beds, which dip to the north through the centre of the island, dip south along the northern seaboard. (Between Seaview and Whitecliff Bay on the east coast the dips are south, horizontal, and 70° north). The Tertiary beds are thus folded into a syncline along an east and west axis.

The dips in the Lower Tertiaries and Chalk are northerly and very steep (up to 90°) along the central axis of the island. The Lower Cretaceous beds, which dip to the north below the Chalk, occupy the south centre of the island,

while the higher Cretaceous strata crop out again on the downs behind Ventnor, dipping to the south and forming a conspicuous outlier.

The structure is thus revealed as a monoclinal fold, striking east and west, flanked by a syncline on the north and an anticline on the south. The central part of the anticline has been denuded away, the oldest beds of all being exposed in the core of the anticline, where denudation has proceeded furthest, near Brixton and Brading. There has been a subsidiary buckle in the centre of the island. The monoclinal fold is also continued on the mainland in the Isle of Purbeck to the west.

Faulting is unimportant throughout the island and igneous rocks are absent.

Superficial deposits, which are nearly all of local origin, occur in isolated patches and in the river-beds.

The only obvious economic products are Brick earth and Chalk (flints for road metal and lime for building).

The structure of the island is illustrated by two typical sections north and south through the island; the vertical scale is exaggerated three times.

Note how all the chief streams, the Yar, the Medina and the Brading, flow north, cutting completely through the Chalk escarpment. The Brading in particular, which is only three-quarters of a mile from the sea near Sandown, turns north for four miles through the Chalk escarpment to reach the sea near Bembridge. This is due to the fact that the rivers were in existence before the initiation of the folding. They have thus been able to keep pace with the folding in the excavation of their valleys. Such drainage is known as 'antecedent', and is also characteristic of the rivers cutting through the Chalk escarpments of the Chiltern Hills and the North Downs.

All the three streams mentioned above are dip (consequent) streams and probably at one time formed tributaries of a large river that flowed eastward, occupying the present site of the Solent and Spithead. This was most likely a continuation of the present River Frome, which now reaches

the sea at Wareham. Other tributaries were probably the Christchurch Stour and Avon, the Itchen (Southampton), and the Arun. Subsequent encroachment by the sea has separated the Isle of Wight from the mainland and excavated the estuary of Southampton Water.

Note how the railways follow the lines of least resistance through the gaps in the Chalk escarpment.

The coast erosion is interesting.

The backbone of the island is composed of the Chalk escarpment, which is prolonged to form the headland of Culver Cliff at the east end of the island, and a four-mile stretch of sea cliff between Freshwater Gate and the Needles. The Foreland and other headlands at Cowes and Hamstead are formed of the hard Bembridge Limestone, the only Tertiary building stone in the British Isles. The bays in the southern half of the island have been eaten out of the easily eroded Weald Clay and Ferruginous Sands.

Apart from the industrial town of Newport at the topographic centre of the island, all the population is engaged in agriculture or catering for the tourist community.

EGTON (YORKSHIRE)

Sheet 43 (*Drift*)

This map represents a region of elevated moorland, rising to 1419 ft. above O.D. The watershed runs east and west and the rivers drain north and south.

The map, which is a 'Drift' one, shows an area in the Cleveland Hills, composed of a conformable sequence of strata extending from the base of the Lower Lias to the top of the Middle Oolite. Some of the minor lithological divisions, such as the sandstone in the Oxford Clay series, are of local development only and are indicated in wedge-shaped fashion in the marginal index. Their impersistence is not of sufficient importance to be classed as an unconformity.

The most striking features geologically are the lozenge-shaped areas of Lias, north and south of the watershed. A

study of the index to strata reveals that the oldest beds are in the centres of these areas and that they therefore represent inliers.

Further, it will be found that these inliers occupy the river valleys and that their lower boundaries point towards the mouths of the rivers. This latter feature is also emphasized by the zigzag outcrops of the Calcareous beds and Moor Grit along the southern margin of the map; in every case this outcrop will be found to tongue *up* the ridges and *down* the valleys. The structure is thus anticlinal from north to south.

It is also to be noticed that newer and newer strata come to the surface towards the south-east corner of the map, and with decreasing altitude. It is obvious that there is thus an easterly dip as well, so that the structure is revealed as part of a dome, dissected by river valleys giving rise to inliers. This radial dip is confirmed by the very few dip marks seen on the map. The sinuosity of the outcrops indicates that the dip is flat.

Note also the outliers of the Calcareous beds, left after denudation on the watershed.

Minor dip faulting has taken place subsequently to the deposition of the Lower Calcareous Grit, since that is the newest horizon seen to be affected by it.

Post-Oolite igneous activity is shown by the intrusion of the (Cleveland) dyke in the northern and eastern parts of the map. Its outcrop runs in a perfectly straight line across country, quite irrespective of the geological outcrops, and is sometimes obscured by drift. *Note* that the dyke is separated from the solid strata in the marginal index.

Important superficial deposits in the form of boulder clay and gravel have been deposited. These have evidently been carried from the north and have swept up the valleys, obscuring the outcrops of the solid strata. They have either never been laid down over the central area, or have been removed by subsequent denudation.

Geologically recent denudation has produced the gorge along which the Whitby and Pickering railway runs; this is

quite possibly a glacial overflow channel of the Derwent river system. Apart from this the drainage is 'super-imposed,' having been initiated radially after the folding of the area.

Important iron-ore deposits occur in the Middle Lias on the extreme west of the map, while coals (probably of no economic value) occur in the Estuarine series. The Alum Shales in the Upper Lias are associated with the Jet Rock for which Whitby is famous. Limestones are valuable for various purposes, and peat affords material for local fuel.

Only in the more fertile areas occupied by the glacial deposits is there any concentration of population.

Some difficulty may be found in drawing sections across this map, owing to the fact that elevations are only indicated by hachuring and by 'spot heights' on the summits of the hills, and not by ground contours. It will be found, however, that if the base of one valley is inserted diagrammatically and the strata indicated with their approximate dips, the floors of the other valleys will fix themselves automatically, as their relative depths are determined by the number of strata exposed in the inliers. The almost identical shades of yellow used for different strata carry distinctive letters.

OXFORD

Parts of Sheets 236, 237, 253, 254 (*Drift*)

The area shown on this map is composed essentially of a sequence of Jurassic and Cretaceous strata which, according to the marginal index, follow each other in conformable order and have been tilted to dip slightly towards the ESE. This results in exposure of the oldest rocks—the Great Oolite—only in the extreme north-west corner of the map, and the outcrop of newer and newer beds as we travel from west to east. Portlandian rocks do not occur west of Oxford.

The conformity of the strata, as indicated in the marginal index, is more apparent than real. For instance, the Shotover beds, which should normally underlie the Lower Greensand, are never found in such a position. The Lower Greensand, when present, rests either directly on the

Kimeridge Clay, as at Boarshill, or on the Portlandian, as at Nuneham Courtenay. The Gault, too, is transgressive, and rests indiscriminately on the Lower Greensand (Nuneham Courtenay), the Shotover Sands (Great Milton), the Portlandian (Baldon), or the Kimeridgian (Chiselhampton). The Cretaceous are, therefore, transgressive over the Jurassic, but, owing to the fact that the strike is much the same in both cases, the unconformity is not conspicuous in the section.

The dissection and denudation of the region, consequent on the development of the complex river system of the Upper Thames and its tributaries, have left numbers of isolated hills, forming the local watersheds between the various streams. These are generally capped by outliers of the more resistant rocks, such as the Corallian, Portlandian and Lower Cretaceous. In some of these outliers, e.g., at Shotover and Boarshill, the low angle of dip, which is very rarely specifically stated, is shown by the close approximation of the outcrops to the ground contours.

The hills are often still further capped by beds of Plateau Gravel. Unlike the Valley Gravels, these are largely of glacial origin. In view of their general trend it is reasonable to suppose that they have been brought through the Cotteswold escarpment by the gaps made by the Windrush, Evenlode, &c.

Relatively unimportant dip faults (downthrown to the west) cause slight dislocation of the outcrops between Wheatley and Islip.

The chief interest in the map, however, lies in the evidence it affords of the physiographical evolution of the river system of the Thames.

In addition to the river's present mature valley there are indications of at least four previous stages in its development in the shape of River terraces.[1]

[1] *Note* that the river terraces are numbered on the map in the reverse order to their deposition. The highest, or first formed, is numbered 4, the lowest, or last formed, is numbered 1. Some terraces, whose age is not known, are not numbered at all.

The fourth, or first formed terrace, is the highest in altitude and varies between 260 and 326 ft. above O.D. The distance from the main river is little indication as to age. At Sandford, three miles south of Oxford, the fourth terrace is within three-quarters of a mile of the river, at Long Hanborough three miles from the main river, but only half a mile from the Evenlode. When more than one terrace is present, however, this one is always the farthest inland of the four. The third terrace varies in altitude between 226 and 260 ft. above O.D., the second between 200 and 258 ft. The first, or last formed, is always found adjacent to the river itself, or as islands in the river alluvium ; it never has terraces of earlier date nearer to the river than itself. It varies in altitude from 172 to 227 ft. above O.D.

Note the almost complete absence of terrace deposits on the concave bank between Shifford and Eynsham, and between Iffley and Abingdon.

The following further physiographic features of the river system are worth noting :

(1) *Erosion on the Concave Bank*

Thames. West of Appleton and east of Abingdon.
Cherwell. Between Islip and Oxford.
Thame. Almost everywhere south of Waterperry.
Evenlode. West of Bladon.

(2) *Cut Offs*

' Cut offs,' where the river has not yet abandoned its old channel, are seen in the Thames east of Stanton Harcourt, perhaps the island of Wolverton, in the Thames valley at Chiselhampton and Cuddesdon, and in the Windrush at Hardwick. Impending ' cut offs ' are seen in the Evenlode on the extreme edge of the map and in the Thames at Eynsham bridge.

It is not impossible that the small dip stream running through Fyfield and Marcham may eventually cut off the whole of the Oxford meander, though the Evenlode and Cherwell would still occupy the valley through Oxford.

(3) *Abandoned Meanders*

Thames. East of Stanton Harcourt and at Cassington (*vide* remarks on Wolverton above).

Cherwell. East of Marston, where the alluvial flat is now devoid of streams.

Thame. Ickford.

(4) *Stolen and Abnormal Drainage*

Ot Moor, on the northern margin of the map, now drained by the River Ray and tributaries of the Thame, probably originally drained through the dry valley at Woodeaton into the Cherwell.

The drainage north of Water Eaton is peculiar. It looks as if the Cherwell originally flowed to the west of the island of Oxford Clay, and that the mile of river west of Islip Mill originally flowed in the other direction as part of the tributary river Ray.

CORK (IRELAND)

Parts of Sheets 186, 187, 194, 195 (*Drift*)

This map may, at first, prove difficult for the student to interpret on account of the large amount of drift present; but if the outcrops of the solid rocks below the drift, as indicated by the broken lines, are considered alone, the structure will soon become apparent.

The area consists entirely of Old Red Sandstone and Carboniferous rocks, which have been folded along an east and west axis into a series of anticlines and synclines. Acting on the hypothesis that the oldest rocks are generally found in the centre of the anticline, and the newest in the centre of the syncline, it is reasonable to suppose that the Old Red Sandstone forms the anticlines and the Carboniferous the synclines. This structure is confirmed by a glance at the dip marks. *Note also* that the dip is always steep, seldom less than 45° and often approaching the vertical. There are also subsidiary folds within the main folds, e.g.,

the anticline bringing up the Carboniferous slates at Ringaskiddy (Cork harbour).

Observe that the anticlines form the higher ground, the synclines the valleys. It will be evident with a little consideration that this is only possible when the dips are steep. (The slight tapering of the two main folds, south of Cork, indicates that the folds pitch slightly to the east.)

The tapering outlier of Carboniferous rocks immediately north of Cork city is of the nature of a very elongated basin.

The faulting is mainly in the direction of the dip, and the displacement of the outcrops due to such faulting is clearly shown. Between Ballygarvan and Queenstown there are no less than six step faults, all downthrown to the east. The pair of faults immediately east of Queenstown, however, represent a small trough block, being downthrown in opposite directions. Few of the faults are seen completely traversing the folds. One or two in the neighbourhood of Cork and Ballygarvan, as well as the one through Blarney, illustrate the principle that the outcrops of the two limbs of the anticline are nearer together on the downthrow side of the fault, but in the syncline wider apart. (Other faults, such as those in Great Island and the Whitegate promontory, show lateral displacement, indicating that there has been horizontal as well as vertical movement.) The oblique fault north of Midleton causes repetition of the Carboniferous rocks in a NW.–SE. traverse.

Superficial deposits, in the form of Glacial Sands and Gravels, and of Boulder Clay, have evidently at one time completely covered the area. At the present time they are chiefly preserved in the valleys, having been denuded off the higher ground. The direction of movement of the ice, as shown by the glacial striae, has been from west to east —from Macgillicuddy's Reeks in the Killarney district. Deposits of 'head' are accumulated round the coastal headlands.

The physiography of the area is extremely interesting.

Note primarily that all the higher ground is composed of the more resistant Old Red Sandstone, all the lower ground

of the Carboniferous. These latter beds, particularly the limestone, are far more liable, not only to mechanical destruction by jointing, &c., but also to chemical solution, than the more resistant sandstone.

Note also how, for the same reason, the headlands are all formed of the sandstone, while the bays, and particularly the whole of Cork harbour itself, have been eaten out of the limestone.

The rivers, originally flowing from the uplands in a southerly direction, have subsequently, with their tributaries, hollowed out their courses in an east and west direction, along the softer strata in the synclines. East of Cork the River Lee turns at right angles to cut a gorge through the Old Red Sandstone in a consequent direction.

This latter gorge, and the one south of Midleton, may be due to faulting ; they can hardly be accounted for as glacial overflow channels, as the ice movement has been in the wrong direction. Two such incipient fault valleys are seen traversing the Whitegate promontory in the south-east corner of the map.

The city of Cork is built almost entirely of the Grey Limestone of the Carboniferous series, while the glacial deposits afford gravel and clay for brickmaking.

HOLY I.

Sheet 4 (*Solid*)

The map represents a coastal area in Northumberland, entirely composed of Carboniferous rocks. The district is wholly agricultural, there being no mineral wealth or other factor to induce a concentration of population.

In general, the trend of outcrops is north and south and newer and newer strata are found as we proceed from west to east, so that the beds strike north and south and dip towards the east. The oldest strata—the cementstone group—crop out in the extreme south-west corner of the map, and along a north and south line between Holburn and Chillingham. In this latter area they are flanked on either side by the

newer Fell Sandstone group. An anticlinal structure is therefore deduced in this area, which supposition is confirmed by the dip marks.

Subsequently to the folding, the Whin Sill (intrusive quartz dolerite in the index) was injected into the Carboniferous strata. Its sill-like nature is shown by the fact that the outcrop follows approximately the strike of the beds, in which it occasionally shifts its stratigraphical horizon. For instance, at Shepherdskirk Hill it lies in the Fell Sandstone group, whereas at Easington it has risen as high as the Middle Limestone group; indeed in the latter neighbourhood it occurs at several horizons simultaneously.

There is also a dyke traversing the Carboniferous strata from Bowsden on the west to Holy I. on the east. In distinction to the Whin Sill this is a narrow vertical-sided intrusion, which runs quite straight across country irrespective of the outcrops of the various strata. Both the dyke and the sill are thus post-Carboniferous in age.

The regularity of the Carboniferous outcrops has been interrupted by a complicated system of faults of post-Carboniferous age. These faults cause the outcrops to swing round, so that on the coast, between Beadnell and Seahouses, the beds actually strike east and west.

The faulting is mainly in the direction of dip, but at least one important fault runs north and south in the direction of strike from Lowlynn Mill to Chillingham. The effect of this has been to repeat the whole Carboniferous sequence, older beds being brought up to the surface on the right-hand side of the fault. The fault is, therefore, downthrown to the west.

The dip faults are particularly interesting. Their general effect is to shift the outcrops, and between Chattonpark Hill and Shepherdskirk Hill there are as many as seven step faults, all downthrown towards the south—the outcrops being shifted in the direction of the dip on the upthrow side of the fault. The fault south of Chattonpark Hill, however, is downthrown to the north, so that this and the fault to the north of it constitute a small trough block. Other step faults

occur east of Doddington. Small faulted outliers occur in the north-west corner of the map.

Note that the fault system is later than the igneous rocks, since both the Whin Sill and the dyke are shifted by it.

The coloured superficial deposits consist of peat accumulations, alluvium in the river-beds and coastal flats, together with raised beaches and blown sand round the coast. A comparison of this map with the Drift edition will indicate to the student how little of the structural geology is really determinable from surface observations, and how much must be deduced by inference and from information derived from mine shafts and well records.

The coast erosion is particularly instructive. Where the coast line runs parallel to the dip, it is a firm continuous line, but where it runs at right angles to the dip across the edges of the strata it is very irregular, owing to differential erosion in rocks of different hardnesses. The harder igneous rocks have resisted denudation and stand out as headlands; they are entirely responsible for the preservation of the Faroe Is. and Goldstone Rock.

It is possible that wave erosion, coupled with the backwash from northerly currents, sweeping against the Faroe Is., have been responsible for the separation of Holy I. from the mainland, and for the subsequent silting up of the area.

The only economic products of any importance are the limestone, for lime and rough building work, indifferent coals (the best coal seams occur in the Coal Measures, not in the Carboniferous Limestone group), and the igneous material for road metal.

OSWESTRY

Sheet 137 (*Solid*)

(This map should be studied in conjunction with the adjoining Sheet, Wrexham, No. 121 (N.S.))

The area represented is that of a mountain region of the Welsh border-land. It is composed of Lower Palaeozoic rocks, truncated on the east by the escarpment of the Carboniferous

Limestone, to the east of which the ground slopes gently towards the low-lying plain occupied by the Coal Measures and Trias.

This map has been selected for description on account of the very remarkable unconformities displayed at the base of the Carboniferous and Trias.

The Lower Palaeozoic rocks are folded into a main anticline of Llandeilian rocks, flanked on the northern and southern limbs by the steeply dipping Caradoc, Ashgillian and Silurian beds. The folds strike east and west, so that newer and newer beds come to the surface as we proceed away from the centre of the anticline in a northerly or southerly direction.

The oldest rocks of all in the area—the lowest Llandeilian and ? Llanvirnian—occur in the centre of the anticline at Craig-y-Glyn. Their position is not entirely a normal one, for although they occupy their correct position in the stratigraphical sequence, they are actually brought to the surface by block faulting, and thus occur as a closed inlier, completely bounded by faults.

The upper boundary of the Llandeilian is largely a faulted one along the Tanat valley, while a minor synclinal structure in the Vyrnwy valley causes repetition in the Caradoc beds south of Llanymynech (south centre of map). *Note* also the minute synclinals along the southern margin of the Llandeilian beds.

Note the exceedingly steep dips in the majority of the Lower Palaeozoic rocks, the unexpectedly wide outcrops being due to the rolling of the major folds.[1] The dips in the Silurian beds are generally flatter, so that the outcrops tend to follow round the contours in the south-west corner of the map.

Note also the directions of cleavage, as opposed to those of dip, in some of the Lower Palaeozoic rocks.

The Carboniferous rocks strike almost due north and south, and dip gently eastwards, so that newer and newer beds are exposed at the surface as we travel from west to east down the dip slope. The dip is generally flat and rarely exceeds 25° in the Carboniferous rocks, so that the outcrops tend to follow the ground contours.

The outcrop of the Carboniferous Limestone, which everywhere forms a marked escarpment, cuts transgressively across the folds of the Ordovician strata, and even across the Silurian in the extreme north centre of the map. The beds appear to thin out northwards, as the Basal Shales are not exposed north of Llawnt. There is, further, a local unconformity at the base

[1] Note that the Carboniferous and Trias are drawn to scale in the marginal index to strata, while the Ordovician and Silurian are not.

of the Erbistock beds of the Upper Coal Measures north of Oswestry, shown by the thinning out of the Coed-yr-allt beds.

Dip marks are rare in the Triassic rocks, but it is evident from the trend of outcrops—on almost level ground—that the strike is rather more easterly than in the Carboniferous. The dip rarely exceeds 15°.

The unconformity at the base of the Trias is further shown by the way the Bunter transgresses the Upper and Lower Coal Measures, the Millstone Grit and the Carboniferous Limestone, to rest on the Caradoc, as its outcrop is traced from north to south. *Note also* the absence of the Silurian beds along this line of outcrop ; they were evidently never deposited, or have been denuded off before the Trias were laid down.

An incipient synclinal or basin-shaped structure is shown in the Keuper beds on the eastern margin of the map.

The chief faulting in the district appears to run in two directions. The first is approximately NW. and SE., the second being approximately at right angles to this.

The former set of faults, therefore, traverses the Lower Palaeozoic rocks in approximately the direction of dip, and has the usual effect of displacing the outcrops. One of this series of faults, with an easterly throw, is responsible for bringing in the Silurian rocks along the northerly margin of the map. A particularly fine trough fault is enclosed by the two chief faults of this series near Llangedwyn. A small but well-defined trough fault is also seen in the centre of the northern outcrop of Llandeilian rocks and a small horst block at its eastern end.

The second set of faults, which is largely restricted to the Carboniferous, has a similar effect in displacing the outcrops in those beds. South-west of Oswestry no less than six step faults occur, all downthrown to the north (or west).

There are also one or two faults running due east and west. The largest of these, the Tanat valley fault, has the effect of a strike fault, cutting out the Cwmclwyd Ash at the top of the Llandeilian. Two faults of this series form a small trough subsidence in the Carboniferous on the northern margin of the map. The faulted inlier of Craig-y-Glyn has already been referred to.

Several of the faults terminate against the outcrop of the Trias, but one at least of the east and west series is seen to cut them, while there is also minor dip and strike faulting which is undoubtedly post-Triassic in age.

Intrusive igneous rocks consist of Dolerite, Volcanic Breccias and Keratophyres.

The dolerite is a composite sill of post-Llandeilian age. Its

outcrop follows closely that of the strata it has invaded. It appears at as many as three different horizons in the same latitude, and it is shifted by the faulting.

The breccia and keratophyre fill the necks of extinct volcanoes. These latter are roughly circular in outline, like plutonic bosses, only very much smaller in size. They are evidently post-Silurian and pre-Carboniferous in age. Two of the volcanic necks carry Roches Moutonnées.

The Cwmclwyd and other ashes and lavas are contemporaneous and interbedded with the strata in which they lie.

The superficial deposits, not being inserted in colour, are not sufficiently conspicuous to merit attention.

The watershed of the district is formed of the high ground occupied by the Llandeilian rocks, which in this case is anticlinal in structure. The main rivers follow the axes of the folds and run in the (partly synclinal) beds of the Silurian and Upper Ordovician. This is still more marked in the River Dee, which flows along the Llangollen synclinorium in the adjoining sheet to the north.

The mountainous part of the area consists of moorland. The Lower Palaeozoic country of the Tanat and Vyrnwy valleys, together with the Triassic plain to the east, form fertile agricultural land, while the only concentrated population occurs at Oswestry in the neighbourhood of the now-deserted collieries. Mineral veins are indicated in the Carboniferous Limestone and Trias.

STOKE-ON-TRENT

Sheet 123 (*Solid*)

This map represents the Potteries Coalfields of the Central Midlands. The surface is composed entirely of Carboniferous and Triassic strata. The Coal Measures and Millstone Grit form the higher ground in the centre and eastern part of the area, which slope away gently to the low-lying Triassic plain to the west.

The Carboniferous rocks as a whole strike north and south. A study of the succession of strata with their respective dips reveals that they are folded into two anticlines and one syncline. The oldest beds of the sequence—the Millstone Grit—are thus exposed in the core of the eastern anticline at Stanley, while the newest—the Keele Group—are developed in the trough of the syncline at Newcastle. The dips are steep, up to as much as 56°. A further feature that will be noticed about the Coal Measures is that, apart from complications due to faulting—to be noticed later—their outcrops follow a roughly zigzag

course, the synclinal fold pointing to the north and the two anticlinals to the south. As there is not much variation in the surface relief, we may infer that the folds pitch southwards.

Subsequently to the folding and denudation of the Coal Measures there was submergence, and they were overlain unconformably by the Triassic beds. The unconformity is magnificently displayed in the way the Triassic strata wrap round the Coal Measures, the outcrop of the Bunter beds transgressing successively every member of the Coal Measure series, to rest on the Millstone Grit east of Longton, as its base is traced round the map. On the western margin of the map, where the strike of the Carboniferous and Trias is nearly the same and dips are not stated, no unconformity is apparent; the junction in this area between the Trias and Carboniferous is also very largely a faulted one.

It is almost certain that the Triassic beds were originally deposited over the whole area, since relics have been preserved from denudation as outliers on the Millstone Grit, north-east of Burslem.

The order of the Triassic beds, revealing newer and newer strata as we travel outwards in all directions from the centre of the map, as well as the dip marks visible, indicate that they have been subsequently elevated into a dome-like structure. The Coal Measures have, of course, also been affected by this post-Triassic uplift.

The unconformity is emphasized by the fact that the dip in the Triassic rocks is much flatter than in the Coal Measures; in the extreme south-east corner of the map they are horizontal. The unconformity is indicated in the marginal index to strata.

Important faulting has affected the area. Surface faults are shown in white, underground ones, deduced from mine information, in brown. In many cases the amount of the downthrow is stated in yards alongside the fault outcrop. It is interesting to note that in the underground faults a throw of up to 200 yards is quite common, while one fault near Longton actually has a throw of 250 yards.

The main faults run both in the direction of dip and strike. The position is, however, further complicated by the fact that the strike faults are not parallel to the axes of the folds, so that at their northern ends they become dip faults.

The dip faults, well seen in the Black Band Group between Longton and Silverdale, have the usual effect of displacing the outcrops sideways. The dip fault which runs north-west from Silverdale towards Bettley, traverses the anticlinal axis of one of the folds, and it will be noticed that the outcrops of the Black Band Group are wider apart on the northern than on the southern

side of the fault (the continuity of the Black Band Group on the west of the axis being interrupted by the strike fault running through Audley). This fault, therefore, is downthrown to the south.

The two main strike faults, east and west of Newcastle, in addition to shifting the outcrops in the Black Band Group, have caused double repetition of the Red and Grey Series in an east and west direction, and given rise to faulted inliers near Newcastle.

In some cases the dip faults appear to be later than the strike ones, which abut against them. *Note also* that both sets of faults are continuous through the Triassic series and are, therefore, post-Triassic in age. The Trias themselves are repeated along the southern margin of the map by the main Newcastle fault.

One igneous dyke is noticeable, running north and south, east of Whitmore. From the fact that it cuts the Trias and is parallel to the main Newcastle fault, we may deduce that it is probably contemporaneous with the faulting and post-Triassic in age.

The boundaries of the glacial deposits are shown by dotted lines.

The structure is well brought out in the published section. Two divisions in the Bunter series are here indicated, which are not differentiated on the map itself. The unconformity at the base of the Trias might have been more clearly indicated. A characteristic feature of the section is the way the harder and less easily eroded grit bands have been indicated as ridges. This is information derived from actual field observation and could not be deduced from a study of the map itself.

It is interesting to note that the anticlines form the higher ground; otherwise the physiography is not particularly instructive.

Economically, the district owes its importance to the Coal Measures, which provide not only the coal seams themselves, but such important products as Ironstone, Gannister, Fire Clay, Brick Clay, Building Stone and Paving Flags. Most of the public buildings in towns situated on the Coal Measures are constructed of Coal Measure Sandstone, while the Pottery Clays of the area are world famous. To the south and west are the fertile agricultural lands of the Trias. The Triassic beds are one of the best water-bearing horizons in Britain, while it is from the Keuper Sandstones to the west of Crewe that all the important salt deposits are obtained.

TEIGNMOUTH

Sheet 339 (*Drift*)

This sheet need not be described in detail; it has been included here as presenting one or two characteristic features.

Firstly, note the relationship of the Cretaceous to the Permian and Trias.

The Permian and Trias dip gently eastwards in the direction of the newer beds. The Cretaceous and Eocene, on the other hand, rest almost horizontally, their outcrops following closely round the ground contours; they form outliers on the highest ground. There is thus a very marked unconformity between the Trias and the Cretaceous, actually the whole of the Jurassic being missing. The Chalk, which does not occur west of Beer (Devon), is also absent between the Upper Greensand and Eocene.

Note secondly, the relationship of the igneous to the sedimentary rocks.

To the east of Dartmoor the outcrops of the Spilites and Diabase are roughly related to the ground contours and surface outcrops. They do not, therefore, represent dykes and it would be reasonable to suppose that all were of the nature of sills, were the spilites, &c., not stated to be contemporaneous in the marginal index to strata. These latter occur at several horizons and must be inserted in the section as interbedded with the strata in which they occur.

The dolerite is intruded into the Permian near Bishopsteignton, and is, therefore, post-Permian in age. It is not seen in contact with the Cretaceous or Oligocene.

The Dartmoor Granite is evidently a boss. *Note* the extensive metamorphic aureole surrounding it. This extends to the Carboniferous and the Permian, but not to the Bovey Tracey beds; the granite is not seen in contact with the Cretaceous. Furthermore, the dolerites are altered by it. The granite is, therefore, post-Permian and post-dolerite in age. It is not possible to fix its age more precisely than that from the information on the map.

The Bovey Tracey beds occupy a unique position in British stratigraphy. They form an extensive outlier occupying a basin, and are quite unrelated as to outcrop to the Cretaceous beds, or to the other strata with which they are in contact. They have been determined by their fossil flora to be Oligocene (freshwater) in age. They form, in fact, a lake deposit of Tertiary age, consisting of an accumulation of clay and other detritus, washed down from the neighbouring granite hills.

The diversion of the River Teign from a subsequent to a consequent direction in the neighbourhood of Newton Abbot, and the origin of the Exe Valley, with the extensive sand bar at its mouth, are other interesting points to speculate on.

Additional Maps for Description and Section Drawing

Abergavenny	Sheet 232 (N.S.).
Alnwick ..	Sheet 6 (N.S.).
Swanage ..	Sheet 343 (N.S.).
Carmarthen	Sheet 229 (N.S.).
Chesterfield	Sheet 112 (N.S.).
Flint ..	Sheet 108 (N.S.).
Swansea ..	Sheet 247 (N.S.).

INDEX